Bats in Vancouver, BC

Who, where, why, and how can we help?

Ocean Leaders Internship Report
City of Vancouver and Vancouver Board of Parks and Recreation
Prepared by Daniel Forrest & Julia Craig

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For Angela Danyluk, Emily Dunlop, The City of Vancouver and The Vancouver Board of Parks and Recreation

September 13, 2023

THE UNIVERSITY OF BRITISH COLUMBIA
Institute for Resources, Environment and Sustainability
Faculty of Science

CITY OF VANCOUVER

VANCOUVER BOARD OF PARKS AND RECREATION

Foreword

This project is the result of Daniel Forrest's internship with the City of Vancouver and the Vancouver Board of Parks and Recreation, as well as Julia Craig's master's thesis at the University of British Columbia's Institute for Resources, Environment & Sustainability (IRES). Daniel is a PhD student in the Connected Human and Natural Systems (CHANS) Lab and the Mitchell Multifunctional Landscape Lab (M2L2) in IRES. Julia is a recent graduate of the IRES MSc program. This project was funded by the University of British Columbia's Ocean Leaders Program (a grantee of the Natural Sciences and Engineering Research Council (NSERC) CREATE program), the City of Vancouver, and Julia's NSERC master's fellowship. This work aims to contribute to the City and Park Board's 100-year vision for a citywide, connected ecological network by identifying characteristics and locations of bat-supporting habitats, and plausible interventions to support bats and their benefits to people.

Large cover photo of Vancouver, BC at dusk taken by Julia Craig.

Inset photo courtesy of the Utah Division of Wildlife Resources.

Positionality Statements from the Authors

Daniel Lipshutz Forrest

I am a settler, Ashkenazi Jew, and cisgender man, now living on xʷməθkʷəy̓əm (Musqueam), Sḵwx̱wú7mesh (Squamish), and səlilwətaɬ (Tsleil-Waututh) land ("Vancouver, British Columbia, Canada"). I was born and raised in Cheltenham, PA, USA, a suburb bordering the City of Philadelphia. Throughout childhood, I formed a relationship with the few remaining streams and forests nestled between roads and buildings near my home, spurring a love and care for nature. This care turned to concern through my public school and undergraduate education as I became aware of the climate and ecological crises. Cheltenham and North Philadelphia are also areas with major socioeconomic inequality and inequity in access to urban nature, related to racial, ethnic, and other identity axes. Spending my childhood there made me directly aware of and concerned with environmental and social injustice before I had the language to describe it.

As an adult, I've lived throughout North and West Philadelphia, PA, USA and Moka and Malabo, Bioko, Equatorial Guinea. Now, having lived in xʷməθkʷəy̓əm, Sḵwx̱wú7mesh, and səlilwətaɬ territories for just 2 years, I have a limited experiential understanding of the socio-econo-cultural context and history, and I have tried to supplement that through reading, conversations with lifelong and long-term residents, and ongoing education. Living across multiple urban contexts shed light on commonplace practices which appeared to coincide with simpler ecological communities, e.g., deforestation, eurocentric landscaping practices, and large amounts of uncontained food waste. Understanding and addressing the inequity in access to dwindling urban biodiversity underpin my current research.

Julia Craig

I am a cisgender woman who lives in Vancouver, which is unceded xʷməθkʷəy̓əm (Musqueam), Sḵwx̱wú7mesh (Squamish), and səlilwətaɬ (Tsleil-Waututh) land. My family history includes European descendants who have both emigrated to Canada several generations ago and more recently. I was born in Mississauga, Ontario, which is part of the Treaty and Traditional Territory of the Mississaugas of the Credit First Nation, The Haudenosaunee Confederacy, the Huron-Wendat and Wyandot Nations. I grew up visiting the Credit Valley River (Missinnihe) and Lake Ontario (Niigani-Gichigami), where I discovered a love for nature at the same time as I learned about how human activity has imperiled it. I received a very Western and science-based education during my undergraduate degree which informed my approach to my master's project. While I studied bat activity in what is now Vancouver, I primarily focused on gathering baseline data on bat species and discovering how the landscape affects them. Due to scope, time, and approach limitations, I did not study the intersections between biodiversity and social conditions, though I hope that my work can be used as a layer to understand the inequities of the city and improve its condition, both for people and nature.

Executive Summary

Highlights

- **Motivation**
  - The City of Vancouver, in line with the Vancouver Plan and the 100-year Ecological Vision that informs the Plan, aims to articulate a future ecological vision for the City of Vancouver
  - To contribute to this vision, the City seeks to identify what changes could be made to better support nature, including wildlife and people
- **Why Bats?**
  - We focused on bats in this study because:
    - Bats control pest and disease-carrying insect populations
    - Half of bat species in BC are considered species at risk
    - Bats populations indicate the health of insect and plant populations
  - Currently, little is known about urban bats and how urban habitats do (and could) support them
- **Methods**
  - Julia Craig, M.Sc. biked throughout the city and detected bats with recording device
  - Bats were identified by their call type and frequencies
  - We related bat detections to urban environmental variables using statistical models
- **Results**
  - At least 10 species of bats occur in Vancouver and Richmond, BC
  - The most abundant species are generalists (e.g., little brown and big brown bats)
  - Forested green spaces and freshwater bodies capable of supporting high insect densities likely host the greatest abundance and diversity of bats
  - Active and passive human activity, including traffic and other sources of noise and light, likely exclude bats from some otherwise viable habitats
  - Surprisingly, low-frequency bats were found to be positively associated with industrial areas
  - The diversity of habitats in the region (including forested parks, open parks, ponds, lakes, wetlands, houses, bridges, and other potential bat roosts) likely contributes to the relatively high diversity of species found here
- **Recommendations to support bat abundance and diversity**
  - ***Create or improve the quality of forest, forest clearings and edge habitats*** (e.g., savannah or meadow-like areas adjacent forests)
  - ***Create or improve the quality of freshwater bodies and surrounding vegetation*** to help bats drink water and eat insects
  - ***Maintain or create roosting habitat*** (e.g., mature trees, old buildings)
  - ***Reduce light and noise in preferred bat habitats*** (e.g., near freshwater, near dense, diverse, and tall vegetation)

Executive Summary

Urbanization is one of the key drivers of biodiversity loss, and urban residents increasingly lack access to green spaces in growing and densifying cities. The City of Vancouver aims to address these concerns across multiple City initiatives, most recently summarized and collated in the Ecology Chapter of the Vancouver Plan. The City seeks to realize this vision: “Vancouver has reshaped its relationship to nature and restored its ecological health to the benefit and resilience of all”. They aim to accomplish this by embedding nature and its benefits in their planning, making space for urban nature, and providing greater access to nature for all residents. To inform and achieve this type of planning, the City plans to identify, rehabilitate, and connect ecological systems in Vancouver. Here, we use bats as an exemplary group to identify existing supportive ecosystems (bat “hotspots”), areas that could or currently connect those ecosystems, and interventions which might help contribute to both of the aforementioned.

Bats represent an often overlooked but important indicator species for ecosystem health and biodiversity. They depend on healthy insect populations (a result of sufficient, quality insect habitat), clean freshwater, and roosting habitats, and thus, their populations reflect the health of all of the aforementioned. Moreover, bats directly benefit urban residents by controlling vectors for disease and agricultural pest insects. However, little is known about the ways that bats exploit novel urban habitats and how bat communities change as a result of urbanization. This is especially true in Vancouver, BC, where few bat surveys have been done, and none, to our knowledge, have been conducted throughout residential, commercial, industrial, and other non-forest or park habitats prior to this study. Here, we surveyed for bats throughout the cities of Vancouver and Richmond, BC using a novel acoustic bicycle transect method. We then statistically modeled the relationship of bat detections with urban landscape and environmental variables across two bat functional groups (see glossary) to 1) understand how they respond to urban land uses and 2) infer and recommend interventions that may enable a greater diversity and abundance of bats in the city.

We found that at least 10 species of bats occur in Vancouver and Richmond, BC out of the 15 species confirmed to occur throughout British Columbia. The most abundant species are generalists (e.g., little brown and big brown bats), which can best make use of the novel and varied resources provided by the Metropolitan area. Green spaces and freshwater bodies capable of supporting high insect densities likely host the greatest abundance and diversity of bats. Human activity, including traffic and other sources of noise and light, likely exclude bats from many habitats, including areas that would otherwise be viable to bats (e.g., a small tree-filled park with a pond, which is surrounded by lots of street lights, high-rises, traffic, and nightlife). Yet, bats were also found in unexpected areas. For example, detection of low-frequency bats (larger, less agile species) was positively associated with industrial areas; however, more research would be needed to determine whether characteristics of industrial areas benefit bats, or if they only attract bats from nearby high-quality habitats, but do not benefit their populations. Moreover, the diversity of habitats in the region, including 1) forests, 2) open parks and other areas with sparse trees (e.g., golf courses, cemeteries), 3) naturally-occurring and artificial freshwater bodies, 4) paths and roads through and adjacent to forests, and 5) natural (trees, rock crevices) and built (bridges, buildings, storage hangers) roosting habitats, likely contributes to the relatively high diversity of species found here.

The following types of interventions are likely to support a greater abundance and diversity of bat species: 1) create or improve the quality of forest, forest clearings and edge habitats (e.g., savannah or meadow-like areas adjacent forests), 2) create or improve the quality of freshwater bodies and surrounding vegetation to support bat hydration and insect foraging, 3) maintain or create viable roosting habitat, and 4) reduce light and noise in preferred bat habitats.

The remainder of this report elaborates on all of the aforementioned, including specific recommendations for how to manage the urban ecosystem to support healthy bat communities and their benefits to people, while supporting the other needs of people.

Introduction

Urbanization is one of three key drivers of terrestrial biodiversity loss, alongside deforestation and agriculture. As we lose biodiversity in cities, we also lose its benefits to people, like supporting the resilience of ecosystem functions (e.g., air purification, temperature stabilization, and water filtration), cultural significance, and benefits to mental health. In recognition of the importance of urban nature, the City outlined a set of directions and policies which aim to embed ecosystems in city planning, make space for and protect nature, and provide access to nature in the Vancouver Plan (The City of Vancouver 2022). Part of the effort outlined in the plan includes identifying, rehabilitating, and connecting ecological systems in Vancouver. The Vancouver Plan builds on nearly a decade of city and park planning for nature, beginning in earnest with the Biodiversity Strategy (2016). During this time, the Park Board and City have identified and indexed some of the critical habitat types and features within its borders, but they have just begun to document the occurrence of species and/or amass these data from researchers. Moreover, little research documenting the relationship of species with people, other species, and their environment has been done in collaboration with the City. This project aims to contribute to this end.

This mid-term report aims to summarize a project that first monitored bat activity in Vancouver and Richmond, BC and then statistically modeled the influence of urban landscape variables on bats. This work identifies existing suitable bat habitats and describes some of the characteristics that likely underlie their suitability to bats. It also highlights areas that may serve as priorities for ecological restoration or rewilding, and suggests feasible interventions to support more bats, their benefits, and the ecosystems that support them.

Relevant Background

Why bats?

Bats represent an often overlooked but important “indicator species” (see glossary) for ecosystem health and biodiversity. Their populations show high sensitivity to changes in the abiotic environment, including land use change typically associated with urbanization. They are also sensitive to pesticides and other toxins due to bioaccumulation from the consumption of prey insects, and changes in their abundance may reflect changes in populations of arthropod prey species and all of the species on which they depend (e.g., plants). Therefore, bats serve as an indication of the populations of many species “lower on the food chain” (i.e., lower trophic levels). Moreover, bats provide critical benefits to people in cities, controlling mosquito and other pest insect populations, thereby preventing the spread of vector-borne diseases and losses to urban and urban-adjacent agriculture.

However, bats have been historically understudied, likely due to their nocturnality, inconspicuousness, ostensible silence, and stigmatization (e.g., a hyperbolic fear of bats as disease vectors, aggressive animals, etc.). This is especially true in urban areas, where their presence is often only obvious when people’s desires conflict with their behavior, e.g., when they roost in unwanted places. As a result, relatively little is known about bats in cities, including which species live in them, which ones are thriving, which are merely surviving, and why (Russo and Ancillotto 2015).

What do we know about urban bats' ecology?

Yet, a small urban bat ecology literature does exist. From these few studies, urbanization has been shown to change bat community composition, leading to a greater abundance of generalist species which can make use of the novel and varied resources provided by cities (Russo and Ancillotto 2015). A global trait analysis suggests that urban-tolerant species tend to have low echolocation frequency, longer call durations, smaller body size, flexibility in roost selection, greater tolerance to disturbance, and can consume a greater diversity of prey insects (Wolf et al. 2022). However, we should expect individual cities' bat communities, including Vancouver's, to differ from these global trends, due to their specific biogeoclimatic conditions, biotic, abiotic and built environments, human practices, and policies.

Factors that influence the presence of bat species in urban environments include the prevalence of adequate roosting sites (Kunz 1982, Kunz and Fenton 2005, Russo and Ancillotto 2015), availability of foraging habitats (Fukui et al. 2006, Nakamoto et al. 2007, Threlfall et al. 2012, Rowse et al. 2016), morphology (Norberg and Rayner 1987) and echolocation characteristics (Neuweiler 1984, Norberg and Rayner 1987, Schnitzler and Kalko 2001, Denzinger and Schnitzler 2013). Therefore, we might expect to see a higher abundance of small-bodied, generalist bat species (those that are flexible in roost and prey selection). We also might expect to see more bats near 1) suitable foraging habitat (e.g., areas that have heavy insect densities) and 2) suitable roosting sites (in 'wilder' spaces, these are often caves, cliffs, crevices, and trees, but in the built environment can be buildings, bridges, and other structures).

Bat activity in temperate regions like Vancouver varies seasonally. In the spring, bats emerge from hibernation or return from migration and females are preparing to give birth. In the spring and early summer, females give birth. This begins a period of intense foraging activity for females as they feed for themselves and their young, which lasts from early to late summer. By the late fall, bats are again preparing for hibernation or migration. Most bats known to occur in British Columbia hibernate, so as summer comes to a close, they return to their hibernacula in mines, caves, rock crevices or housing and remain in a state of torpor for the majority of the winter, rarely emerging to feed. Those that migrate, like the Hoary bat, fly south as far as Mexico or Central America to continue feeding on insects year round (Craig et al. 2014).

Low- & high-frequency bats

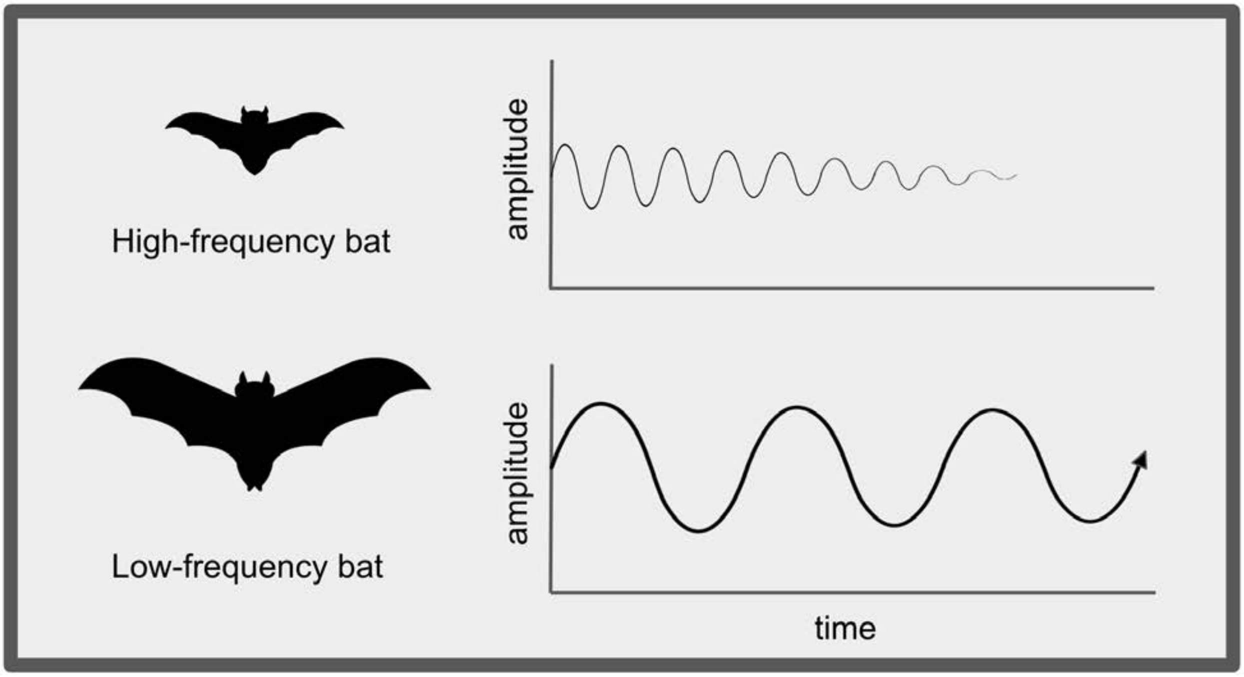

Figure 1. Schematic diagram showing the general differences in morphology (primarily size), call amplitude (loudness), and time (i.e., frequency/pitch) between high- and low-frequency bat species.

We are able to differentiate bats into functional groups (*definition*: bats which tend to behave similarly and respond to similar environmental conditions; also see Glossary) by their call frequencies: high and low. Acoustic detections do not always allow us to reliably identify bats to the species level. However, by differentiating bats into two functional groups, we can get a better sense of the habitats on which each group depends (and if there are key differences), which factors support or undermine their existence in the city, and improve our understanding of the ecosystem types and changes their populations reflect (e.g., an improvement to their utility as indicator species).

High-frequency bat species emit high-frequency calls, which travel faster, but only for short distances (Figure 1). These bats are also small and can quickly change direction in flight. These qualities allow them to navigate a more complex three-dimensional environment, making them well-suited to quickly maneuver among trees and shrubs as they forage for insects and evade predators. Correspondingly, from studies in "wilder" spaces, they have been associated with forested and shrubby habitats, and are not typically found in open areas (e.g., grassland, savannah, shrubland). In this study, high-frequency bats include the endangered Little Brown Myotis, which is most acutely threatened by white-nose syndrome. Importantly, white-nose syndrome was recently detected in British Columbia for the first time (CBC News 2023), stressing the urgency of their conservation.

Low-frequency bat species emit low-frequency calls, which travel slower, but for longer distances, allowing them to locate prey insects at greater distance, but with less precision (Figure 1). From studies in "wilder" spaces, they have been associated with open areas (e.g., grassland, savannah, shrubland), and are not typically found in forested and shrubby habitats. They are larger, and tend to be less maneuverable in flight, opting for more linear flight paths. Together, their morphology and low-frequency calls for echolocation make them well-suited to forage for larger-bodied insects above bodies of water, above and adjacent vegetation, in forest corridors (i.e., naturally-occurring and human-made flight paths in the understory or forest canopy), and in forest clearings.

Methods

We employed acoustic detections of bats collected by Julia Craig, M.Sc., during Spring and Summer 2021 throughout Vancouver and Richmond, BC alongside high-resolution land use/land cover data in statistical models to predict suitable bat habitat in the Metro Vancouver Region. The fully described methods of the acoustic bat surveys and Bayesian hierarchical habitat suitability models can be found in Julia Craig's UBC master's thesis. Abbreviated methods are detailed below.

Bicycle bat surveys

Julia used a novel bicycle transect method, riding through the city at dusk with a bat-detecting recorder mounted at the rear of the bike. Transects were 10-15 km. long and selected to cover the greatest range of landscape variables within the study region (Vancouver and Richmond, BC). Bat activity, temperature, and humidity data were recorded using an Anabat Swift detector and an Elitech GSP-6 Temperature and Humidity Data logger, both mounted at the rear of the bicycle. Transects were ridden at a near constant rate of 18 km/h, monitored by an odometer. She then used bat sound ID software (Kaleidoscope Pro 5.4.2) to identify bats to the species, genus, or functional group (high-frequency or low-frequency calls) level. Due to the lack of reliability in taxonomically identifying bats to the species or genus level, we opted to group bats into the two functional groups: low-frequency (defined here as bats that typically have a maximum call frequency of 35 kHz or less) and high-frequency (defined as bats with a maximum call frequency of greater than 35 kHz).

Environmental data

Environmental data were collected from publicly available sources (see Table 1 in the Appendix for complete definitions and sources). Variables are as follows: land use (10 classes), road type (4 classes based on traffic, road composition, and width), greenness (from a LIDAR image; is a pixel primarily composed of the color green?), tall vegetation (vegetation > 3 m. in height), buildings, light pollution (from a gray-scale NASA satellite image at night, 0 = black, fully dark, 255 = white, maximum brightness), and freshwater bodies (excluding rivers). All variables were calculated as a percentage of buffers with a 25 meter radius around a 25 meter segment of a transect (~3100 sq. m. per buffer). See Table 1 for term definitions and Table A1 for data sources and formatting methods.

These variables represent one set of environmental factors which may influence the presence of bats. However, they also represent our and the data providers' positionality. For example, the land use classification scheme comes from a regional government agency, Metro

Vancouver. The categories they delineated for urban land use types (e.g., residential) reflect the views and policies of Metro Vancouver officials and utility to their decisions, but do not directly reflect any relationship with bats. Rather, bats likely respond to the underlying characteristics that these land uses tend to reflect. We aimed to interpret the findings as such, inferring the underlying mechanisms of bats' relationships with land use from their relationships with other environmental variables and the existing bat literature.

Bayesian habitat suitability models

We built Bayesian mixed-effects models using the `brms` package (Bürkner 2017) in R (v. 4.2.1) to analyze the relative strength of effects of urban environmental variables on bat detection for different bat groupings (all bats, low-frequency species, and high-frequency species). Models were formulated with bat detection per buffer (binary; yes or no) as the response, and environmental variables as a percentage of buffer, as well as some environmentally-descriptive data (season, moon phase, etc.) as the predictors. All variables were centered on their means (mean values becomes 0) and standardized (1 standard deviation of the variable becomes 1 unit change in variable). All models were constructed using a Bernoulli response distribution and a logit-link function.

Model variable definitions

Table 1. Definitions for all variables included in the statistical model. See Figures X-X for examples of the first six land use variables. See Table A1 in the appendix for data sources and methods for data processing.

Variable name	Definition
Forested park	A contiguous park with greater than 50% tree cover.
Open park	A contiguous space, like a park, cemetery, golf course, or airport land, with less than 50% tree cover, but few impervious surfaces (i.e., trees, shrubs, grass and herbaceous plants).
Farmland	Agricultural areas used for growing crops. Tend to be open, with low light pollution, and low human density.
Residential	Land use tracts with detached and low rise apartment buildings and single family homes. Tend to have a mix of mostly impervious surface with some greenery
Industrial	Land use tracts dominated by impervious surfaces, low human population, high human activity, and high light pollution. Includes the Vancouver Port and areas along the Fraser River
Intensive Urban	Land use tracts that are dense and busy areas with mid to high rise buildings for retail, commercial and residential purposes. They feature impervious surfaces, light pollution, traffic and human density.

Tall Vegetation	Vegetation taller than 3 meters.
Greenness	All dense green areas (defined as having a normalized difference vegetation index (NDVI) of greater than 0.6)
River	Locations where the Fraser River overlapped with the study area
Sea	All area where seawater overlapped with the study area (e.g., Salish Sea, Burrard Inlet, False Creek)
Distance from freshwater	Calculated as the distance (in meters) from a transect segment to the nearest source of freshwater (ponds, lakes, fountains, etc.)
Roads	An index whose weight corresponds with the mean traffic intensity of four road types: unpaved path (value = 0), low/no traffic roads (value = 1), residential roads (value = 8), and urban roads (value = 27).
Buildings	The footprint of every building in the city. Does not consider height.
Light Pollution	I.e., Artificial Light at Night (ALAN). The ambient brightness of the city, ranging in value from 0 (total darkness) to 255 (maximum brightness).
Humidity	The % humidity of the air, as obtained by a bike-mounted sensor.
Moon Phase	The fraction of the moon that is illuminated from 0 (new moon) to 1 (full moon)
Season	A binary value of early season surveys (April to May; 0) and late season surveys (July to August; 1)

Results

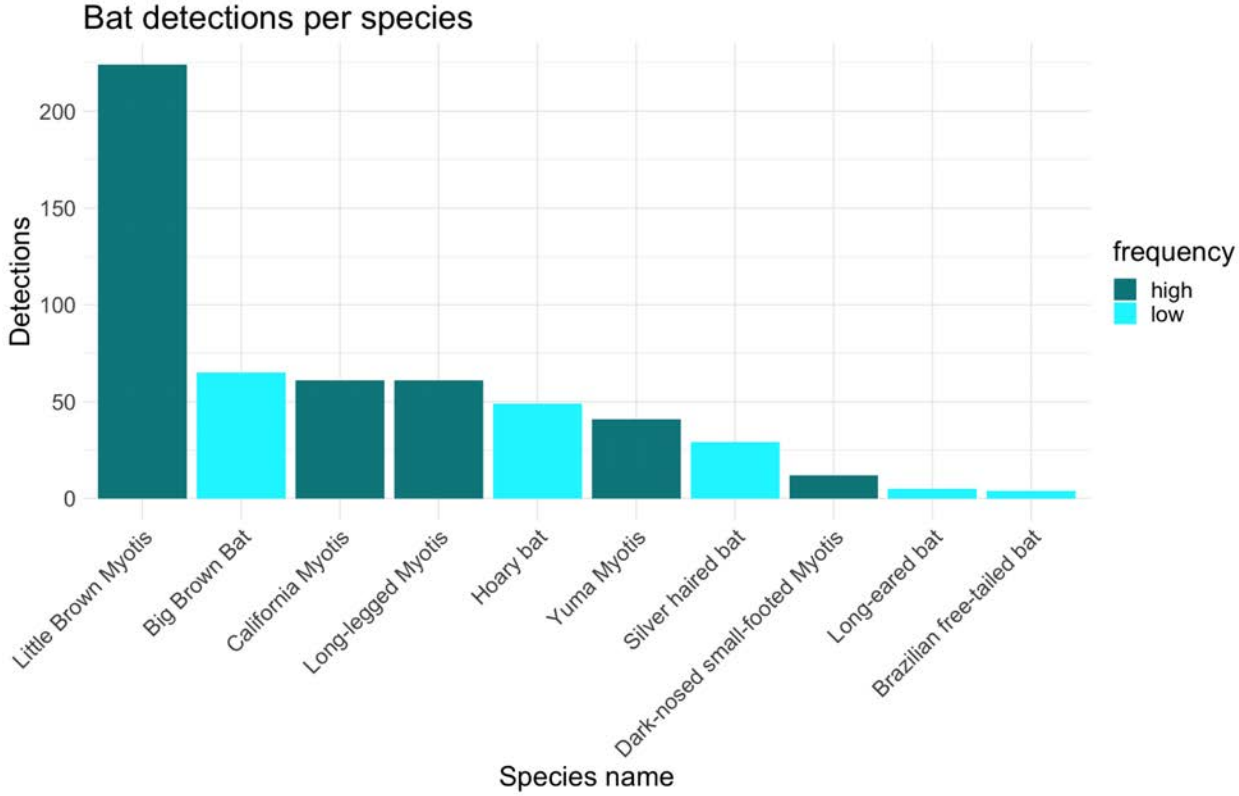

Figure 2a. A bar plot of detections per species, *excluding* unidentifiable calls. High-frequency call species are colored dark turquoise, while low-frequency calls are colored light blue.

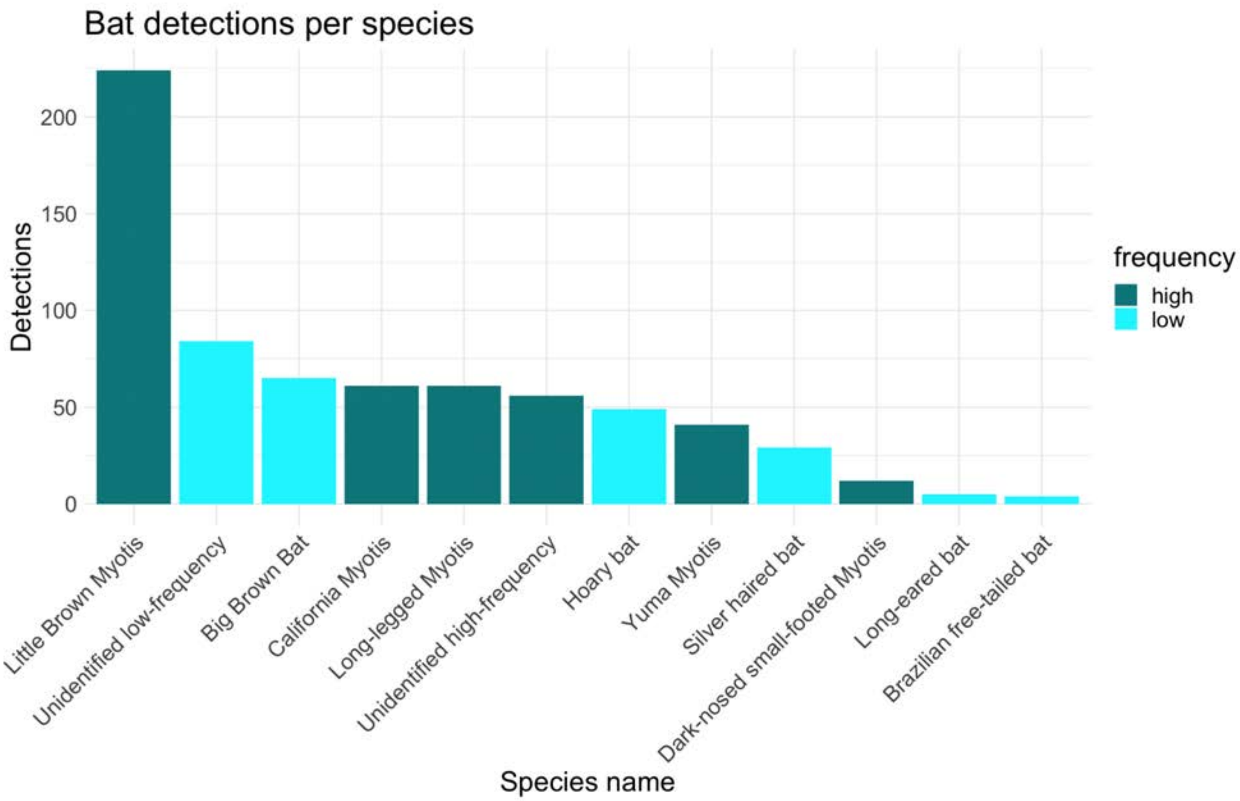

Figure 2b. A bar plot of detections per species, *including* unidentifiable calls. High-frequency call species are colored dark turquoise, while low-frequency calls are colored light blue.

Bat Detections

Julia detected 715 bat passes, of which 236 were low-frequency bats and 455 were high-frequency bats. She reliably identified 10 species, listed here in order of abundance: Little Brown Myotis (*Myotis lucifugus*; high-frequency, 224 detections), Big Brown Bat (*Eptesicus fuscus*; low-frequency, 65 detections), California Myotis (*Myotis californicus*; high-frequency, 61 detections), Long-legged Myotis (*Myotis volans*; high-frequency, 61 detections), Hoary bat (*Lasiurus cinereus*; low-frequency, 49 detections), Yuma Myotis (*Myotis yumanensis*; high-frequency, 41 detections), Silver haired bat (*Lasionycteris noctivagans*; low-frequency, 29 detections), Dark-nosed small-footed Myotis (*Myotis melanorhinus*; high-frequency, 12 detections), Long-eared bat (*Myotis evotis*; low-frequency, 5 detections) and Brazilian free-tailed bat (*Tadarida brasiliensis*; low-frequency, 4 detections), as well as 56 detections of unidentifiable high-frequency bats, and 84 detections of unidentifiable low-frequency bats (Figure 2a, 2b).

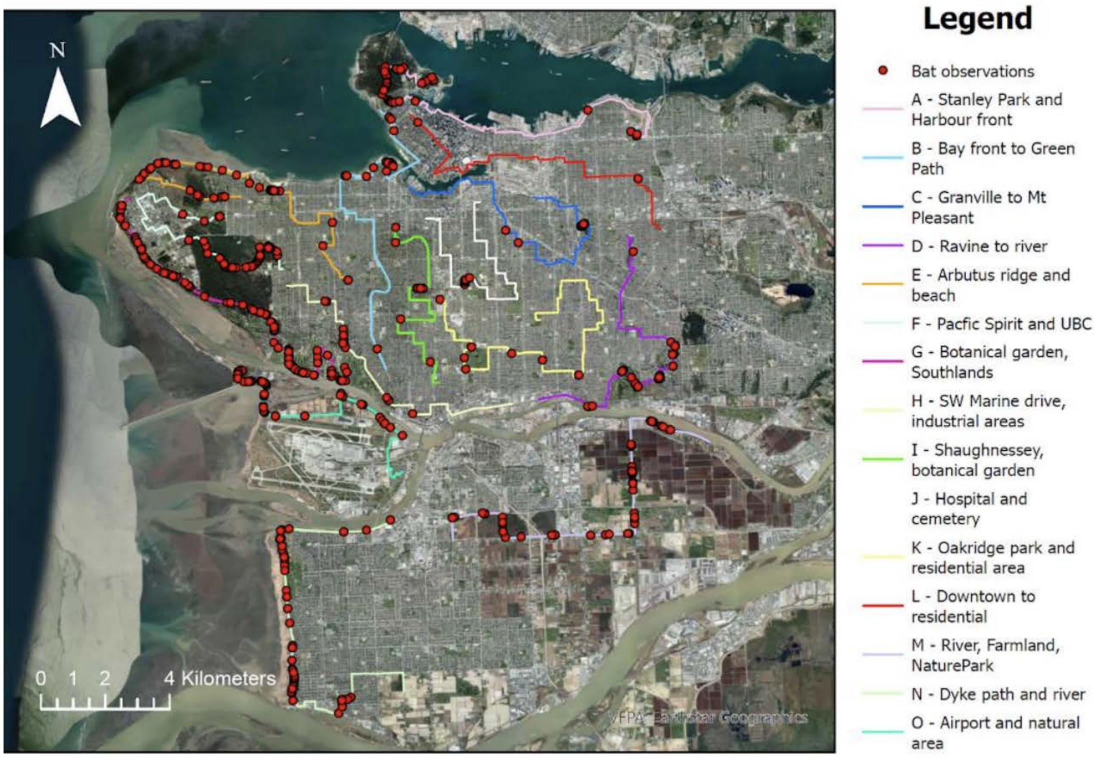

Figure 3. Map showing all acoustic bat detections along the 15 bicycle transects in the study area during the Summer 2021 field season.

From a simple visual inspection, bats detections appear to be clustered near parks and other green spaces, water bodies, coastal and riparian areas, and agricultural lands (Figure 3). However, the relative effect that each of these habitats on bat populations is better understood via the statistical model results discussed next. This is because a visual inspection of spatial patterns can only provide a qualitative sense of land use relationships with bat detections, but does not allow us to 1) understand the effects of other non-land use variables (e.g., artificial light at night, humidity, season, temperature), 2) generate quantitative estimates of the strength of spatial relationships, nor 3) understand the relative strength of multiple variables with bat detections simultaneously.

Statistical models

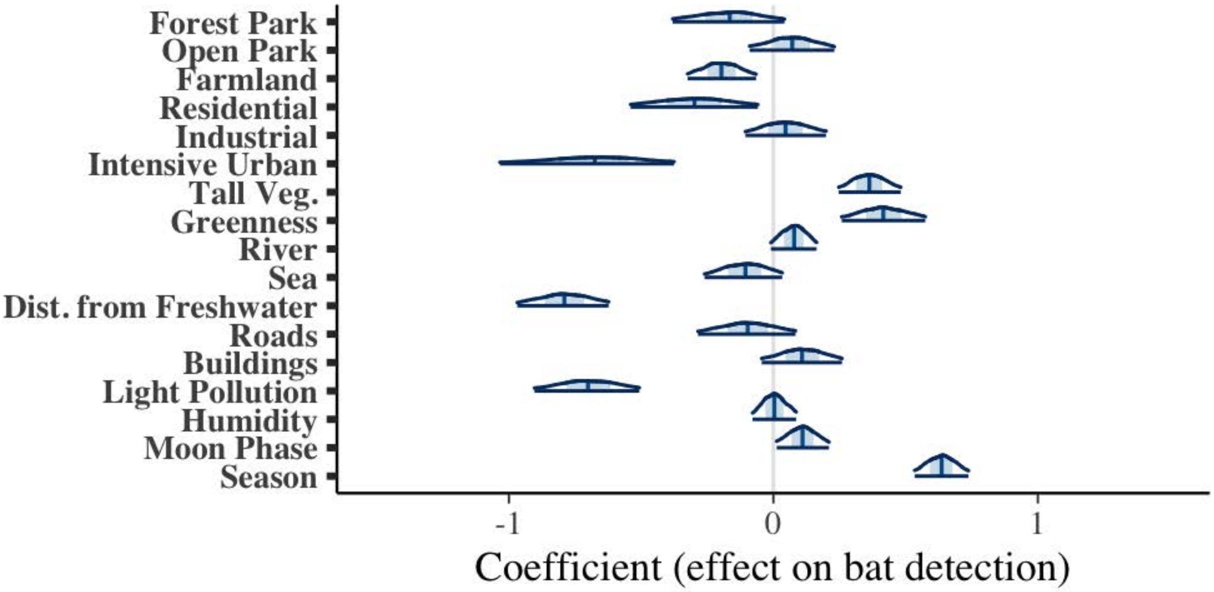

Figure 1. Model coefficient plots for the “All Bats” model. Credible intervals curves show 89% probability region, center blue vertical line depicts the mean estimate, shaded light blue depicts 50% probability region.

According to the “all bats” model, we are more likely to detect bats near tall vegetation, in greener areas, and in late summer. In contrast, bats are less likely to be found near intensive urban areas, light pollution at night, and at greater distances from freshwater. All of these coefficients had near-equal magnitudes, suggesting they have a near-equal impact on the likelihood of bat detections (Figure 1; Table 2). To a lesser extent, bats are not as likely to be found in farmland or residential areas.

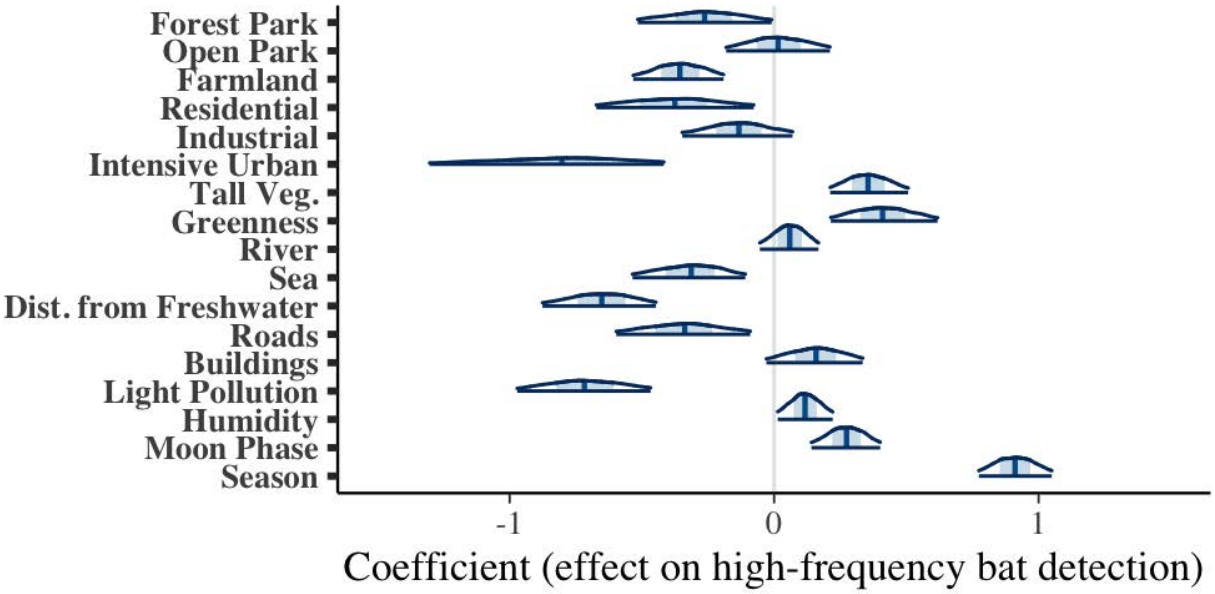

Figure 2. Model coefficient plots for the “High-frequency Bats” model. Credible intervals curves show 89% probability region, center blue vertical line depicts the mean estimate, shaded light blue depicts 50% probability region.

High-frequency bat detections shared all directions of effect with the all bats model, except for being additionally negatively associated with sea, and roads, and positively associated with moon phase (i.e., more bats detected on nights with fuller moons). The coefficient of season had the greatest positive magnitude, demonstrating that high-frequency bats were detected with a far greater frequency in the late summer (late July to early August, second sampling period) than early summer (~May, first sampling period) (Figure 2; Table 2).

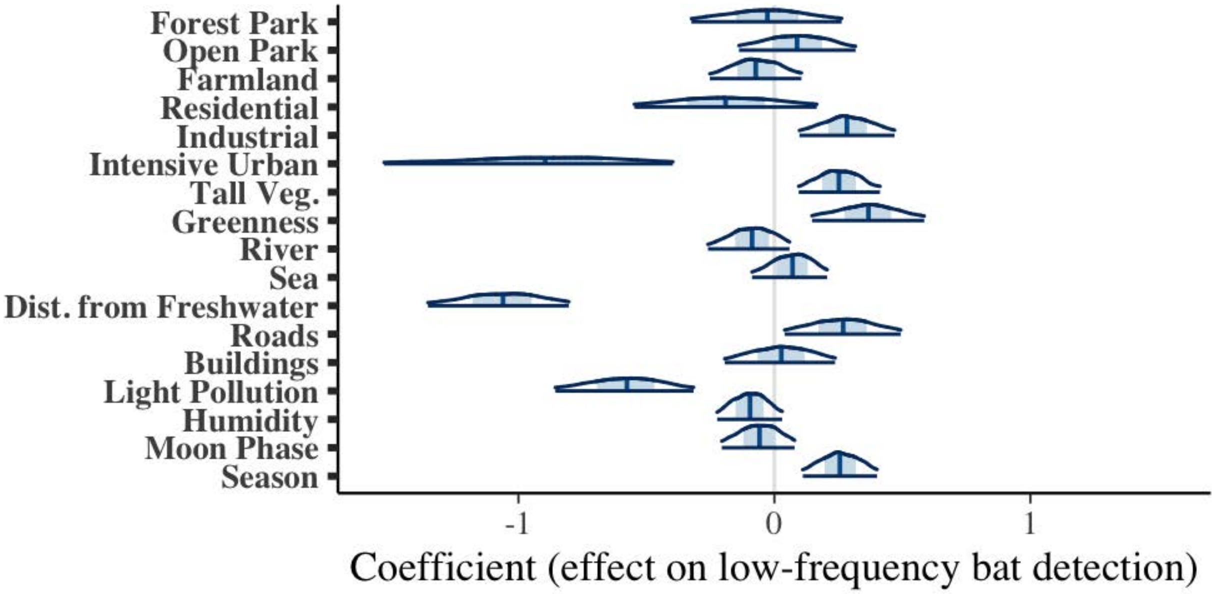

Figure 3. Model coefficient plots for the "Low-frequency Bats" model. Credible intervals curves show 89% probability region, center blue vertical line depicts the mean estimate, shaded light blue depicts 50% probability region.

Low-frequency bat detections shared all of the strong associations with the all bats model, but were additionally positively associated with industrial areas and roads, and had no association with farmland and residential areas. This indicates that a fair number of low-frequency bats were detected in industrial areas and along roads (Figure 3; Table 2).

Quantitatively interpreting statistical models for management recommendations

We can approximate the effect that a change in a given model variable would have on bat detections by exploring the "conditional effects" of variables in the model (if interested in hearing greater detail about this method, please reach out to Daniel Forrest; see end of report for contact information). For example, holding all other things constant, we are most likely to see a bat directly next to a source of freshwater. If we move ~750 meters away from a freshwater source (the mean distance from freshwater in our dataset), we are ~60% less likely to detect a bat. If we travel a total 1500 meters away from a freshwater source, we are 85% less likely to detect a bat.

Similarly, holding all other things constant, we are most likely to see a bat in total darkness. If we then moved to an area that is ~30% brighter, we would be 60% less likely to find a bat. At the maximum brightness in our study area at night ("100%" light pollution), we are 95% less likely to detect a bat than in total darkness.

One of the most dramatic effects is seen via intensive urban cover. Bats are most likely to be detected in areas with no intensive urban land cover. If just 16% of an area is intensive urban cover, we are 80% less likely to detect a bat.

Conversely, we are most likely to see a bat when an area is fully green. We are 220% more likely to detect a bat in a fully vegetated area than in an area without any vegetation.

Mapping Habitat Suitability

- Bats are more likely to be found in and near green spaces (e.g., urban forests, golf courses, cemeteries)
- Bat "hotspots" include Stanley Park, Pacific Spirit Park and surrounding forests, Queen Elizabeth Park, Jericho Beach, Musqueam First Nation, the Southlands and adjacent golf courses, Langara Golf Course, and VanDusen Botanical Garden
- Some tree-heavy neighborhoods and smaller parks may serve as less-than-optimal – but still utilized – foraging grounds, flight corridors, roosting habitat, or areas to drink on the way to preferred habitat
- Low-frequency bats are more likely to be seen directly adjacent to and on paths and roadways near larger green spaces (e.g., Pacific Spirit, Stanley, and Queen Elizabeth Parks), while high-frequency bats make use of more varied habitats and a larger portion of the city, and are likely to be seen weaving around trees and other vegetation

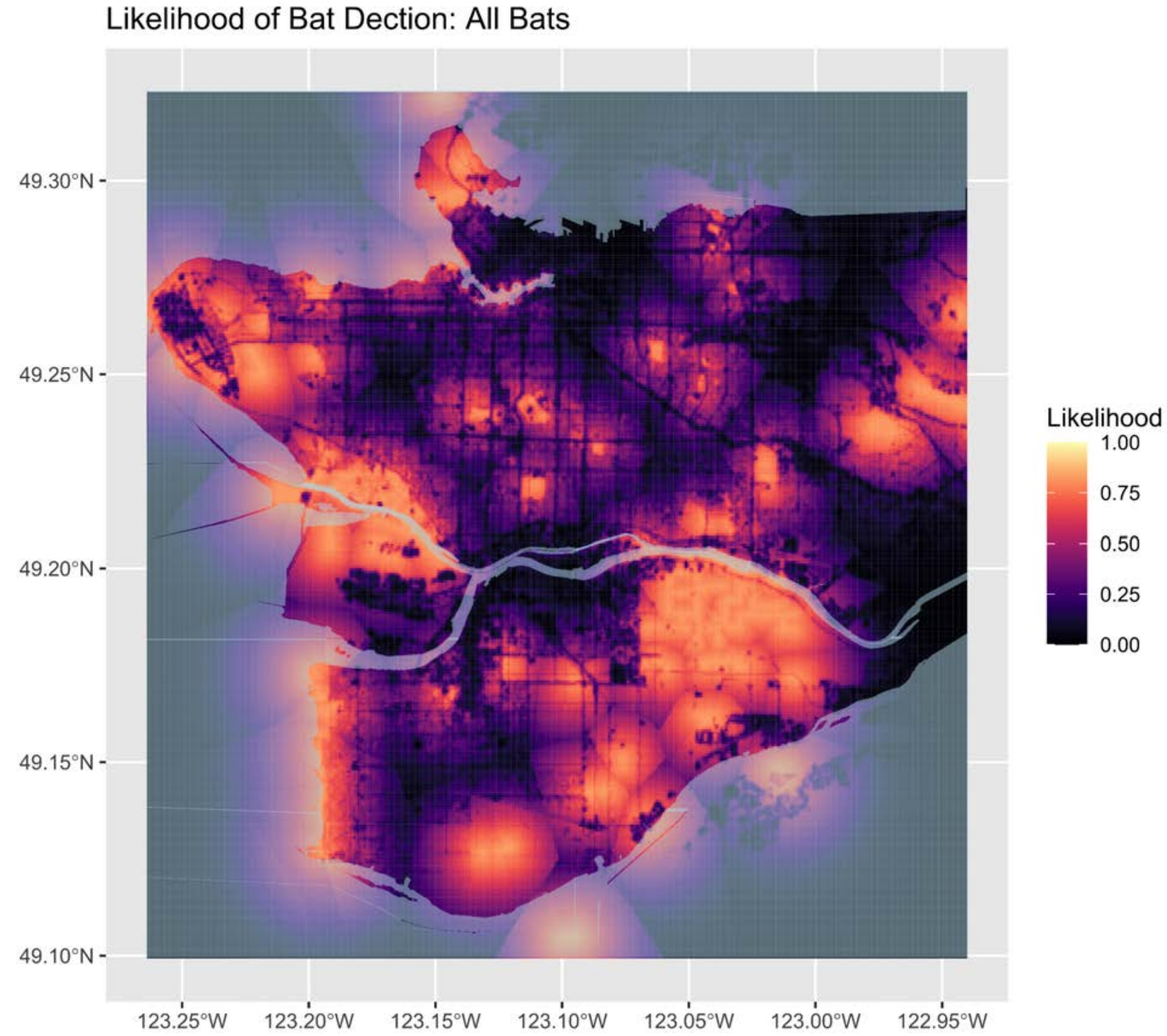

Figure 4. Map depicting model predictions of the likelihood of bat detection across the Metro Vancouver area. Light colors indicate high likelihood of detection, dark indicates low likelihood. The light blue translucent layer depicts rivers and sea. Land area falls within those boundaries, except for the eastern edge.

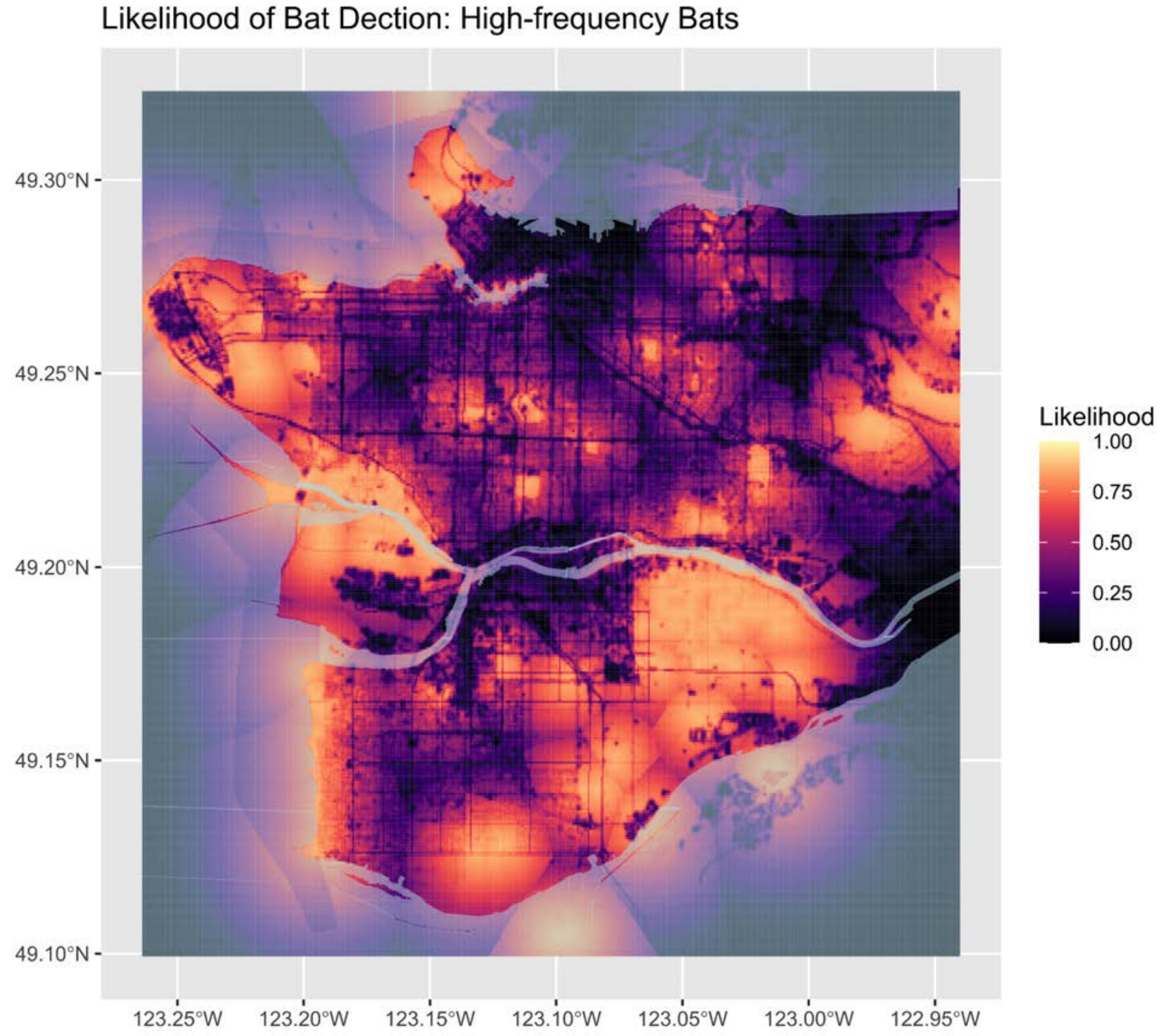

Figure 5. Map depicting model predictions of the likelihood of high-frequency bat detection across the Metro Vancouver area. Light colors indicate high likelihood of detection, dark indicates low likelihood. The light blue translucent layer depicts rivers and sea. Land area falls within those boundaries, except for the eastern edge.

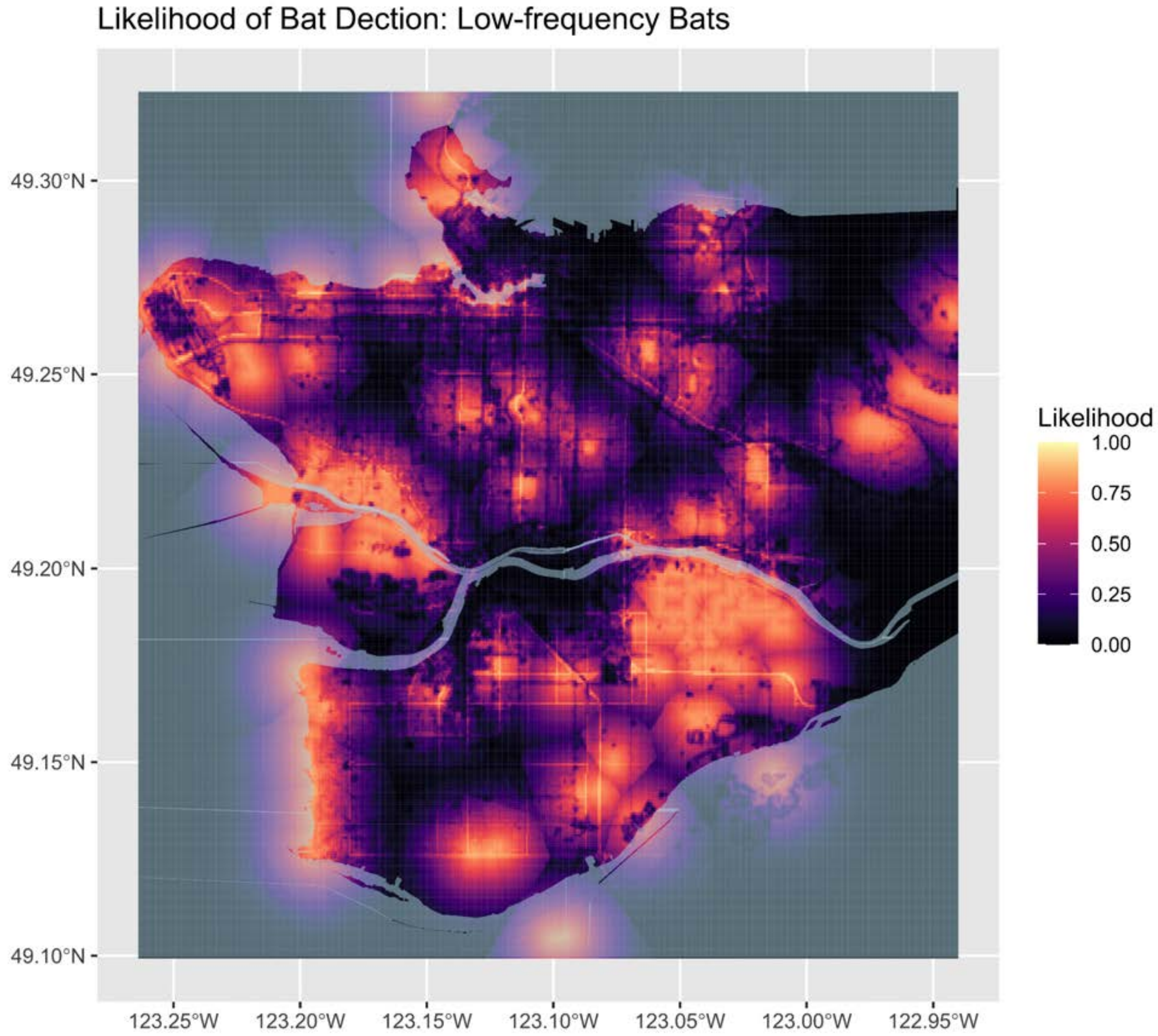

Figure 6. Map depicting model predictions of the likelihood of low-frequency bat detection across the Metro Vancouver area. Light colors indicate high likelihood of detection, dark indicates low likelihood. The light blue translucent layer depicts rivers and sea. Land area falls within those boundaries, except for the eastern edge.

The habitat suitability map produced from the “all bats” model (Figure 4) indicates that bats are more likely to be found in and adjacent to urban forests, golf courses, cemeteries, and other areas with vegetation and freshwater that are not regularly occupied by people. For the purposes of description and communication, I define “hotspots”, somewhat arbitrarily, as greater than 0.75 (out of 1) likelihood of bat detection throughout our surveys (also, see glossary). Some of the Vancouver hotspots include Stanley Park, Pacific Spirit Park and surrounding forests, Queen Elizabeth Park, Jericho Beach, Musqueam First Nation, the Southlands, and adjacent golf courses, Langara Golf Course, and VanDusen Botanical Garden. Richmond hotspots include: the West Dyke Trail and Sturgeon Banks, Iona Park and Sea Island Conservation Area, Richmond Nature Park, and the many golf courses and agricultural lands in south and east Richmond.

There appear to be some suitable corridors (see glossary) and residential areas throughout the region that might maintain connectivity between these hotspots. For example, while VanDusen, Queen Elizabeth, and Mount View Cemetery/Memorial South Park all appear to be “hotspots”, many patches of residential neighborhoods and smaller parks in Shaughnessy, South Cambie, and Riley Park-Little Mountain have likelihoods of detection around 0.5 or greater, perhaps allowing bats to forage, drink, rest, and move between the preferred hotspot habitats. Bats also may travel to these areas for their nightly roost in the attics of houses and other buildings (supported by communications with Aaron Aguirre, UBC bat researcher). Areas surrounding Richmond Nature Park, Savage Creek, Country Meadows, and Mylora Sidaway Golf Clubs (i.e., patches of forest adjacent to agriculture), Garden City Community Park and Arboretum, and more may act as similar habitat corridors in Richmond.

Though hotspots did not vary noticeably between the all bats (Figure 4), high-frequency bats (Figure 5), and low-frequency bats projections (Figure 6), some key differences among frequency groups are made clear via map projections. High-frequency bats appear more likely to travel throughout city neighborhoods between hotspots, whereas low-frequency bats appear to stay closer to very green and forested areas. However, low-frequency bats are more likely to be spotted along roads adjacent to these larger green spaces.

Discussion

Ecological interpretation of statistical models

Table 2. Qualitative summary of the directions of effect of model variables on bat detections. "Strong" modifier indicates a magnitude of effect greater than 0.5. "Weak" indicates a magnitude less than 0.5. See Figures 1-3 above for quantitative model output.

Variable name	**All Bats**	**High-frequency Bats**	**Low-frequency Bats**
Forested park	Neutral	Neutral	Neutral
Open park	Neutral	Neutral	Neutral
Farmland	Weakly negative	Weakly negative	Neutral
Residential	Weakly negative	Weakly negative	Neutral
Industrial	Neutral	Neutral	Weakly positive
Intensive Urban	Strongly negative	Strongly negative	Strongly negative
Tall Vegetation	Weakly positive	Weakly positive	Weakly positive
Greenness	Weakly positive	Weakly positive	Weakly positive
River	Neutral	Neutral	Neutral
Sea	Neutral	Weakly negative	Neutral
Distance from freshwater	Strongly negative	Strongly negative	Strongly negative
Roads	Neutral	Weakly negative	Weakly positive
Buildings	Neutral	Neutral	Neutral
Light Pollution	Strongly negative	Strongly negative	Strongly negative
Humidity	Neutral	Neutral	Neutral
Moon Phase	Neutral	Weakly positive	Neutral
Season	Strongly positive	Strongly positive	Strongly positive

All bats

Several results were common across both groups of bats: tall vegetation (>3 meters) and greenness were positively associated with bat detections, and intensive urban lands, greater distance from freshwater sources, and ambient light pollution were negatively associated with bat detections. The strongly negative coefficient for the intensive urban variable is likely due to the negative effects that low insect densities, noise, light, and human activity and occupancy (including making more noise and light) have on bats (factors common to commercial and the densest residential areas, i.e., “intensive urban”; see Figure 7 for example) (Moretto and Francis 2017). The finding that fewer bats were observed far from accessible freshwater (also observed in Lehrer et al. 2021) likely reflects bats’ dependence on water sources for both frequent hydration and foraging for insects. Ambient light pollution may alienate bats because it makes them visible to both predators (i.e., bats fear being eaten) and prey (i.e., bats have a lower success-rate in eating insects if seen by the insect), and we saw a correspondingly negative association of light pollution with bat detections. Other studies have found that bats take longer commuting routes and fly through darker sections of the city to avoid illuminated areas (Moretto & Francis 2017). The consistent effects that these environmental variables had on bat detections suggests that they are abiotic filters. In other words, bats’ presence and establishment are limited where light pollution, noise, and impervious cover are highly concentrated, and freshwater sources and suitable roosting habitat are scarce. Conversely, their presence is promoted by vegetation and sources of freshwater.

Our results affirmed the importance of green spaces in cities for bats, regardless of park status (see Figures 8 and 9 for clear examples of both). Greenness and tall vegetation were both strongly positively associated with bat detections. However, forested and open parks were not significantly associated with bat detections. Together, these results suggest that bats are supported by areas with more plants and less impervious cover, and that park status neither contributes nor detracts from this effect. In other words, private *and* public green spaces support bats.

In sum, our results suggest that urban areas that are darker, quieter, have more vegetation, and contain (or have nearby) freshwater are likely to be most supportive of urban bat populations, especially supporting critical activities like foraging for insects and drinking water. However, as some of the functional-group-specific results below suggest, other urban habitats (e.g., industrial areas) and the overall heterogeneity of urban areas may also contribute to the abundance and diversity of bat populations in Metro Vancouver. The below discussions details the ways that high- and low-frequency bats may be partitioning the urban landscape, using and avoiding different parts of the city.

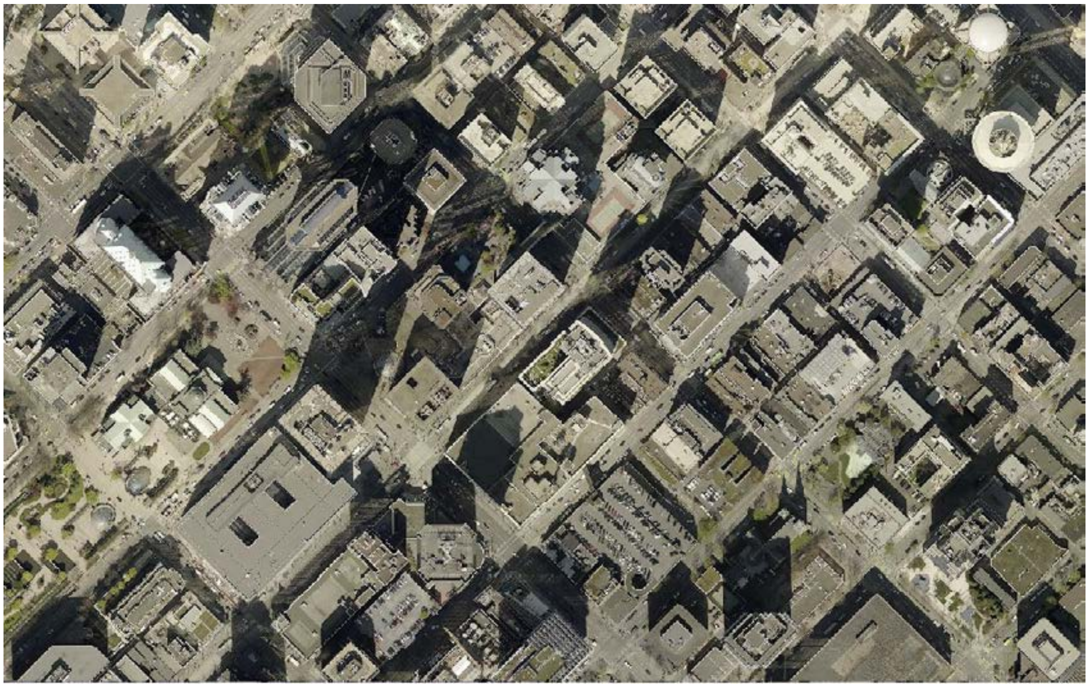

Figure 7. Intensive Urban. Orthophoto of the center of downtown Vancouver, obtained from the City of Vancouver's OpenData Portal.

Figure 8. "Forested Park"; Orthophoto of Stanley Park (with a small portion of Beaver Lake at the top) obtained from the City of Vancouver's OpenData Portal. Primarily consists of forested park land cover.

Figure 9. Forested Park/Open Park/Residential. Orthophoto of VanDusen Gardens (containing forests and a pond), Oak Meadows Park ("open park"), and surrounding neighborhood obtained from the City of Vancouver's OpenData Portal.

Figure 8. Open Park/Residential. Orthophoto of Connaught Park, an "open park", and surrounding residential neighborhood. Obtained from City of Vancouver's OpenData Portal.

Figure 10. Orthophoto of Langara Golf Course and adjacent neighborhood, obtained from the City of Vancouver's OpenData Portal.

High-frequency bats

We found that high-frequency bat detections were positively associated with (in order of decreasing magnitude) season, greenness, tall vegetation, and moon phase, and negatively associated with intensive urban areas, light pollution, greater distance from freshwater, residential areas, farmland, roads, and sea.

These bats are likely to be most active when foraging for insects in wooded or shrubby areas and over small bodies of water situated near vegetation (e.g., aspects of Figures 8 and 9). Intensive urban areas, which primarily consist of impervious cover and buildings, doused with noise and light, are unlikely to host these bats (e.g., Figure 7). We found that high-frequency bats are more likely to be observed in dark, forested or heterogeneous/patchy forest and open areas (e.g., golf courses; see Figure 10) and close to freshwater. They are likely to be significantly more detectable (i.e., more active) late in the summer. There are several possible reasons that the summer season had more bat passes than the spring. In the summer, offspring have been born and many have begun to fly by late July and early August, increasing the number of bats in the sky (Lausen et al. 2022). Furthermore, later in the summer, temperatures are warmer, which has two effects: 1) speeding the reproduction and activity of insects, thereby increasing prey density for bats, and 2) reducing the amount of energy bats must expend on maintaining their high body temperatures (Gilbert & Raworth 1996). Smaller, high-frequency bats may choose to remain in torpor during the colder spring months (when there is also lower prey availability) to conserve energy (Fjelldal et al. 2021).

Low-frequency bats

We found that low-frequency bat detections were positively associated with (in order of decreasing magnitude) greenness, industrial area, roads, season, and tall vegetation, and negatively associated with distance from freshwater, intensive urban areas, and light pollution.

These bats are likely to be most active when foraging for insects in "uncrowded airspace", e.g., above rivers, at forest edges, along roads and paths that create a clean flight-path amidst vegetation (see Figure 11). They too require frequent hydration and likely forage above freshwater sources for insects, hence, their negative relationship with increasing distance from freshwater. Intensive urban areas, which primarily consist of impervious cover and buildings, awash with noise and light, are highly unlikely to host these bats. We found that low-frequency bats are more likely to be observed in open areas (e.g., golf courses, roads, paths) near or adjacent to vegetation and close to freshwater.

Figure 11. Photos of roads and paths near and/or in forests that likely support low-frequency bat foraging taken by Julia Craig.

Additionally, industrial areas may offer an unexpected source of shelter and foraging opportunities for low-frequency bats. They are only periodically occupied by people during work hours (i.e., periods of quiet), they are often adjacent rivers with some remaining riparian habitat, nearby weedy vegetation and pooling water may harbor insect populations, and industrial equipment and storage facilities may offer roosting habitat (Figures 12, 13). Alternatively, they may represent a habitat "sink", which have low insect loads, but good foraging and echolocation space with low human activity for periods. More research would be needed to uncover the mechanisms leading to this result.

Figure 12. Photos of industrial areas surveyed taken by Julia Craig, where low-frequency bat detections occurred. Pictured left, an area along the Fraser River. Pictured right, an area near the Port of Vancouver.

Figure 13. Industrial/River. Orthophoto of industrial land along the Fraser River obtained from the City of Vancouver's OpenData Portal.

Lastly, low-frequency bats, too, are positively associated with season, but less so than high-frequency bats. Low-frequency bats are generally larger than the high-frequency group, which means that they lose less body heat and are able to forage longer than smaller bats (Stawski et al. 2014). Therefore, colder temperatures in early summer (May, June) are less likely to adversely affect these bats than the smaller, high-frequency bats.

Relevance to ecological management decisions

More to "green": which kinds of vegetation support urban bats?

- **Maintaining existing large, mature trees** and **allowing trees to grow to maturity** will support abundant and diverse bat populations by creating healthy insect populations and foraging habitat
- **Increasing the volume of understory vegetation likely** indirectly **supports bats** by supporting insect abundance and diversity
- **A diversity of urban forest types**, from those with very high to low plant densities, **likely helps to support bat diversity**, because:
    - Denser forests with greater structural complexity and denser vegetation likely support high-frequency bat foraging
    - Conversely, forests with lower plant density, or those containing walking and biking paths, and roads adjacent forests likely support low-frequency bat foraging
- Managers should strive for urban forests composed primarily of native plants, because **diverse, native plants** indirectly **support bat diversity** by enabling diverse insect communities

Our models included two simple representations of vegetation: green space (green wavelengths detected from LiDAR imagery) and tall vegetation (> 3 meters). Across all three models, we saw positive associations with both variables, sending a clear signal that bats depend on vegetation, and that vegetation taller than 3 meters, like shrubs and trees, have a specific benefit. A study of the effects of urban vegetation on insectivorous bat occurrence in temperate Australia (Threlfall et al. 2016) corroborates these results, showing that medium and large trees (> 41 cm. diameter at breast height (DBH)) had a positive effect on bat activity, abundance, and diversity.

However, bats' response to urban forest structure (patterns of plant size and density) appears fairly complex and varies by species. Bats require flight paths to forage for insects, but smaller, more agile species (i.e., high-frequency bats) can navigate more cluttered forests than larger species (i.e., low-frequency species). Bats' response to forest structural complexity appears non-linear and likely varies by species (Luck et al. 2013, Suarez-Rubio et al. 2018), meaning forests can be too open and devoid of understory to support many insect prey (Threlfall et al. 2016), but also too cluttered for most bats to forage (Suarez-Rubio et al. 2018). The ideal urban forest for bats appears somewhere in the middle, where ground cover is prevalent, large trees are present, but not many plants are not crowding the airspace between the canopy and ground. Low-frequency bats appear to prefer more open forests, whereas high-frequency bats tend to prefer slightly more crowded forests (Luck et al. 2013, Suarez-Rubio et al. 2018).

Lastly, the presence and diversity of native plants, from herbaceous plants to shrubs and mature trees, tends to be associated with diverse and abundant bat communities (Threlfall et al. 2016).

Overall, this suggests that 1) increasing native vegetation composition, 2) increasing understory vegetation volume, and 3) retaining large trees and planting native trees in places they can grow to maturity are practical management approaches that improve outcomes for urban bats (and also birds, insects, and more!).

Freshwater

- Create **new freshwater features** that are at least 3-30 m. long and 0.75 m wide
- **Enhance water features** by restoring riparian/nearby vegetation
- **Place and/or retain water features strategically** to:
    - minimize flight distances among suitable habitat
    - minimize noise or light at night
    - maximize nearby forest, meadows, and other diverse, native vegetation

Bats depend on sources of freshwater for frequent hydration and forage above freshwater bodies for insects. Bat activity has been shown to be positively correlated with freshwater features in the majority of urban bat studies (e.g., Dixon 2012, Straka et al. 2016, 2020, Krauel and LeBuhn 2016, Lehrer et al. 2021), and our results support this. Interventions which can increase the quality and quantity of suitable freshwater habitat like stream daylighting, improving water quality via the creation of riparian or other water-adjacent habitats (reducing erosion, eutrophication, etc.), or even the creation of artificial ponds, lakes, and possibly fountains, are likely to support the abundance of bat populations. Freshwater features that are at least 3 to 30 meters in length, and at least 0.75 meters wide, depending on species morphology - or flight capabilities - allow bats to more easily drink and forage, as they do so during flight and need adequate space to navigate in and out of the water body (Nunn 2007). However, as further elaborated on below, conditions surrounding the freshwater body, especially sensory pollutants like noise and light, may counter some of the benefits of freshwater to bats. This suggests that water features are best places and/or maintained in areas surrounded by bat-supporting habitats, like forests or meadows containing diverse, native plants

Noise

- **Prioritize areas with low levels of noise pollution** when considering which areas to restore
    - For example, managers may **choose habitats away from** highways, trains, frequent construction, and other **sources of noise** for restoration projects.
- Managers may also consider **modifying the timing of construction projects** and other noise production **to coincide with times** (e.g., day) and seasons (e.g., winter) **when bat activity is low.**

Less is known about bat responses to noise in cities, but in developed and experimental settings, some bat species exhibited limited movement behavior (Bennett and Zurcher 2013), modified echolocation calls (Wu et al. 2017), decreased foraging efficiency (Luo et al. 2015), and habitat avoidance (Bunkley et al. 2017) when encountering urban noise, particularly traffic. Although often synonymous with urbanization, the spatial variation of urban noise is typically overlooked when planning for wildlife habitat in cities (Parris et al. 2018), and its impact on urban bats is uncertain.

Lehrer et al. (2021) directly measured noise among a set of urban environmental variables and its relationship to bat detections, and found a significant negative effect. Though we did not measure the effect of noise directly, intensive urban lands and roads with heavy traffic are likely sources of noise that bats avoid, and we saw correspondingly negative values for both of these in the all bats model. Bats may tolerate intermittent noise if an area has sufficiently high quality foraging habitat or another attract. As we saw in our low-frequency bat model, these bats were positively associated with roads, and we suspect this is because roadsides adjacent parkland act as easy flight and foraging corridors for these larger, less agile bats.

Noise, as a sensory pollutant, may counteract the benefits of other urban habitat features like freshwater and dense, diverse vegetation. The threshold at which urban environments are ‘too loud’ varies depending on bat species, as some are more sensitive to noise and choose to avoid a noisy area, while others may develop hunting or call strategies that adapt to the interference (Finch et al. 2020). There is some evidence that bats can modulate their calls (pitch and volume) to avoid sonic interference from ultrasonic noises (including traffic noise) in the frequency range of bats’ echolocation, but it may have an energetic cost, such that bats may continue to forage in these areas, but may reduce survivorship and fecundity (i.e., reproductive success) (Yantén et al. 2022).

Interventions to directly reduce urban noise may be unrealistic (e.g., prohibiting noisy activities like construction, industrial development or outdoor festivals) or interfere with urban aesthetics or wildlife movement (like creating sound blocks), so managers may wish to instead **prioritize areas with low levels of noise pollution** when considering which areas to restore (Shannon et al. 2016). For example, managers may **choose habitats away from** highways, trains, frequent construction, and other **sources of noise** for restoration projects. Additionally, **managers may consider modifying the timing of construction projects** and other noise production **to coincide with times** (e.g., day) and seasons (e.g., winter) **when bat activity is low**.

Artificial Light at Night (ALAN)

- ALAN, i.e., light pollution, was strongly negatively associated with bat detections in our study
- Many potential options exist to reduce or mitigate light pollution, but evidence in support of any particular intervention is limited. The following options may be implemented, depending on specific contexts and trade-offs
  - **Reducing** light pollution through dimming or turning lights off periodically
  - **Mitigate** light pollution with physical blocks or light-directing strategies

- ○ **Tuning LED lights** to “warmer” frequencies to minimize interference with insects and other wildlife – an option which has little to no drawbacks and some support

Evidence for the effects of light pollution on bats in the literature is mixed. However, in our study, light pollution at night was highly negatively associated with bat detections, especially high-frequency bats. Given that light pollution stood out as one of the largest negative effects on bat detections, while a number of other variables associated with light pollution, like buildings, intensive urban, industrial, and other land use variables, were included in the model, this suggests a mechanistic relationship between light pollution and bats (however, experimental research on this topic would help to better establish a causal relationship and is a worthy pursuit).

Artificial light at night (ALAN) may disrupt bats’ ability to forage and make them vulnerable to predators, as they are more easily seen by prey and predators alike (Cravens et al. 2018). However, some studies (e.g., (Barré et al. 2022, Li and Wilkins 2022) have shown a positive relationship between bats and ALAN. Researchers hypothesize this may result from light attracting and densifying insect prey, facilitating hunting. Aerial-hawking bats (aligning more, but imperfectly, with our “low-frequency” bats) are more likely to benefit from ALAN, as they may be attracted to and consume dense insect populations around some types of street lights and other urban lights (Barré et al. 2022). Gleaning bats, which feed off of vegetation and other surfaces, would not feed on flying insects, and therefore, would likely only serve to detriment from ALAN. The type of lights and frequencies produced likely determine the severity to which it disrupts bats foraging, time of emergence, and/or attraction of insects, but insufficient evidence exists to make any definitive statements about these effects (Stone et al. 2015).

The simplest possible intervention to address ALAN is to avoid lighting areas that support bats, but this may not be possible when other factors must be prioritized (e.g., human safety). Fortunately, a host of other promising, but still unproven, interventions exist, including variable lighting schemes, reducing the intensity of light, changing the type of light, and changing light spacing (Stone et al. 2015). Variable lighting schemes, such as motion sensors or timers which control light activation, may help to limit the duration of light so as to minimize the impact on bats. However, peak human activity tends to overlap with bat activity (e.g., bat emergence at and just after dusk), which may negate the benefits of this intervention. Next, reducing light intensity by dimming lights to low levels that still facilitate human use or controlling the direction of light may represent an easy compromise. Directional lighting schemes may be the more promising of the two, but evidence to support their use is sparse (Fure 2012, Stone et al. 2015). These include any technology that can reduce light spillover into intentionally dark flight corridors, while maintaining light in areas of human use. Strategic placement of vegetation, such as trees or hedges, can effectively minimize light trespass by shielding against the intrusion of light into light-sensitive areas (Gaston et al. 2012).

Recently, many municipalities, including Vancouver, have switched over to using lights which emit greater amounts of “blue” frequencies (e.g., LED or metal halide lamps), because these technologies are more energy efficient. However, these frequencies are more likely to interfere with insect and bat behavior, as these lights attract greater proportions of insects than lower-intensity, “warmer” sodium lights (Stone et al. 2015). Some evidence exists to show that tuning LEDs to lower color temperatures (i.e., warmer or “redder” light) and adjusting to lower spectral frequencies (e.g., ~2700 K) attracts fewer insects (e.g., (Longcore et al. 2015), and therefore, may affect fewer bats, and this represents a fairly easy change to street lighting while maintaining energy efficiency. Lastly, dark gaps between lights, created by intentionally spacing out lights, or alternatively, illuminating only a fraction of existing lights at a time may allow bats to navigate through the dark patches (Stone et al. 2015). However, again, little research exists to test the effectiveness of this option. Altogether more research is needed to test the effectiveness of all of the above interventions to reduce ALAN's impact on bats.

While addressing urban light pollution might appear as challenging as mitigating noise pollution, there exists a broader range of strategies available for protecting an area from excessive light. Managers **may choose from the above recommended interventions** based on the specific context of the area they wish to restore or protect. Managers may **reduce** light pollution through dimming or turning lights off periodically, **mitigate** light pollution with physical blocks or light-directing strategies, and/or tune LED lights to "warmer" frequencies to minimize interference with insects and other wildlife.

Where Bats Call Home: Roosting in Caves, Crevices, and Built Structures

- **Allowing bats to remain in roosts**, including houses, when they are found would help to support bats in the city
    - Public education and familiarization with bats may help to reduce the fear and stigma associated with bats and allow people to share spaces with bats
- **Allowing trees to progress through their life cycle**, including decomposition, would likely support cavity-roosting bat species, like the Hoary Bat.

In "wild" spaces, North American bats typically roost in tree cavities, bark overhangs, rock crevices, or caves. In cities, bats can find roosting habitat in remaining mature forests, rocks, cliffs, or caves, but also find suitable roosting habitat in human-made structures. Bats are known to roost under bridges, in buildings, and other suitable structures. In Vancouver, many generalist species are likely to benefit from the multitude of human-made potential roosting structures. Some species, like the Little Brown Bat and Yuma myotis have been confirmed to roost in buildings (Craig et al. 2014). On the other hand, some species only occasionally roost in built structures. Species like the Hoary Bat almost exclusively roost in tree cavities, sometimes found in live deciduous trees (e.g., knot holes), and often found in dead and decaying trees (both deciduous and coniferous). Allowing trees to progress through their life cycle, including decomposition, would likely support cavity-roosting bat species, like the Hoary Bat (Kunz et al. 2003).

The fact that urban areas have fewer of the more specialized roosting habitats (e.g., rock crevices, mature trees with cavities or bark overhangs) and more human-made roosting structures is likely another force for the simplification of urban bat communities. Little and big brown bats, which both exhibit flexibility in roosting habitat, likely benefit from their adaptability, and we saw that they were correspondingly the two most detected species in this study.

Like foraging habitats, many natural and built structures that would otherwise be suitable for bat roosting may not be utilized due to the presence of sensory pollutants (light and noise) and/or a low-quality surrounding habitat. Allowing bats to remain in roosts, including houses, when they are found would help to support bats in the city.

Prey insect populations as a function of habitat: a biotic filter on bat occupancy?

All bats that occur in the Metro Vancouver Region exclusively consume insects. These bats depend on sufficiently abundant insect populations to support their foraging, i.e., their energetic and nutritional needs.

Poor water quality can severely limit insect populations. One study conducted in Melbourne, Australia found that low levels of sediment pollutants, increased riparian tree cover, and water body size supported higher insect order richness and a greater abundance of Coleopterans (beetles) and Trichopterans (caddisflies), respectively (Straka et al. 2020). In turn, bat abundance was higher in these areas. The maintenance of high water quality is likely critical to bats flourishing. Interventions and management considerations to maintain high water quality include 1) controlling for nutrient and toxic chemical run-off, which can lead to eutrophication and/or water toxicity, respectively, 2) limiting sedimentation via erosion, flooding, construction, or dumping. The maintenance of vegetation buffers around water bodies and/or introduction of nature-based solutions (e.g., rain gardens, bioswales, etc.) and limiting disturbance via development are two key means to maintain or increase water quality, the health of the aquatic ecosystem, and thereby the abundance and diversity of insects and bats it supports.

While many diurnal insects are more abundant in urban than rural areas, nocturnal Lepidoptera (e.g., moths) abundance tends to be lower in urban areas. Yet, moths are one of the preferred prey species for many bats (Kolkert et al. 2020). Lepidoptera primarily feed on plants during their caterpillar life stage, and are often specialized to lay eggs and feed on specific host plants. This is yet another reason that increasing the abundance and diversity of native plants should contribute to bat abundance and diversity. The City of Vancouver has already created a website to suggest native plants capable of supporting native pollinators, and many of these would likely indirectly benefit bats.

Ecological management considerations and recommendations: summary

Maintaining and creating viable habitat

Bats require ample foraging, drinking, and roosting opportunities to survive. While roosting and hibernation (or migration) occur over winter, peak foraging and drinking occur in warmer temperatures (peaking in mid-late Summer). Therefore, insect abundance and access to freshwater sources in summer are critically important to bat survival. In an effort to support abundant and diverse bat populations, the City should aim to maintain or create forested and mixed open/forested lands that contain clean freshwater bodies like streams, ponds, and lakes, and aim for high water quality in those water bodies.

Considering and controlling for sensory pollutants

Overall, abundant light and noise disrupt bats' ability to effectively forage and may disturb them during rest and hibernation. Therefore, light and sound must be considered and controlled when planning for urban bats. Viable habitat, like a small forest patch containing native trees and a pond, may be underutilized by bats if it is surrounded by noise or light pollution. A larger forest area (e.g., Stanley Park), may have noise and light at the edges, but large trees and the sheer size of the park prevent that noise and light from reaching the core of the habitat.

Ecological restoration projects should, therefore, consider the quality of the surrounding environment before advancing a project, and seek to address sensory pollutants in restoration plans. For example, if a manager is considering whether to allow a lowland drainage area to once again flood, restoring a wetland, they may also consider how close the area is to sources of sensory pollution (e.g., the nearest roadway and that roadway's traffic volume, type of streetlights, etc.). Additionally, new developments near viable bat habitats may produce noise and light that disturb nearby habitats. For example, if new high rises and retail were built adjacent to a forested park, the added noise and light may disrupt bats' ability to effectively feed or rest. "Buffer" setbacks (e.g., maintaining 30 m. of forest between core bat habitat and a new development) may mitigate the negative impacts of sensory pollutants on bat foraging and roosting behaviors. These setbacks aim to mitigate (i.e., "buffer") the negative impacts of new developments on natural areas. Further research would be needed to determine recommendations for specific patch sizes, distances, light and decibel levels.

Interactions and cross-scalar needs

Due to the heterogeneity of this region's landscape, the patchiness of preferred habitats, and human activities in this city, bats likely use a wide array of urban habitats throughout the day, year, and their entire life-cycle. Moreover, different species' have varied needs and preferences for drinking, foraging, roosting, and other requirements. Generalists, which we saw in greater abundance, likely make use of the wide variety of habitats on offer in Vancouver and Richmond. Specialists, which tend to prefer more specific insect prey, foraging, and roosting habitat, likely occur in higher abundance where diverse, native vegetation, high-quality freshwater, and certain types of trees occur, in the case of forest-obligate roosting species.

Additionally, interactions among human activities and uses, habitat features, sensory pollutants, and bats likely drive the viability and importance of some city locations over others. For example, an area of forest or other vegetation without a viable source of freshwater for drinking may not support bats, in spite of it otherwise having many of the characteristics bats require, because it is too far for bats to navigate without hydrating. Similarly, bats may avoid an area that has healthy, diverse vegetation and a quality source of freshwater, because it is too noisy or bright. Conversely, we may also encounter bats in an area because it supports just one of the many obligate bat behaviors; namely, insect foraging, drinking, or roosting. Bats may, therefore, navigate across a multitude of urban habitats throughout the day to meet their combined needs. For example, bats may drink from a freshwater fountain in an open area without vegetation as they navigate between foraging or roosting habitats. In light of this, we should consider how an area may support bats, even in "hidden" or less-than-obvious ways, before modifying an urban landscape. A walking/biking bat survey or acoustic-monitoring device may help to assess whether bats use or visit an area, and this information could be taken into account before landscape modifications are made.

Limitations, lessons learned, and future directions

It is important to recognize the limitations of our bicycle transect and modelling approach. First, our surveys occurred during a single field season, so we cannot uncover temporal trends or understand how representative these data are of a typical Vancouver spring and summer. We cannot be certain how representative our detections are of longer time-scales (e.g. decadal) or know the effect of exceptional events. July 2021 was the one of the hottest and driest on record for Vancouver, and temperature records were broken across the province as hundreds of people died (Kergin 2022; CBC 2022). Bats, being sensitive to heat and relying on consistently available freshwater, may have been greatly affected by these heatwaves. However, as summer temperatures in the area continue to climb and rain continues to decrease as a result of climate change, these sorts of events will likely become more common in Vancouver, and thus, our understanding of bat ecology during these events may serve as an important indicator of future bat ecology.

Next, mobile transects to acoustically detect bats are inherently biased towards low-frequency bats and bats flying below canopy cover, as these bats' calls are more easily detected by the recording device. Low-frequency bats are 'heard' by the microphone from a greater distance than high-frequency bats, because their calls are louder and travel farther (Kerbiriou et al. 2019). The obstruction of foliage or other insulating objects also means that the range of the microphone is limited and may not pick up on bats that are foraging nearby but above the canopy, or on the other side of a building, for example.

Another difficulty with acoustic bat identification is that some recordings are less clear than others due to other noise, weak signals from far-away bats, or the lack of distinction of calls among species. For example, Little Brown myotis cannot be certainly identified to species level when they are in cluttered or close environments (if this occurred in our study, the call was considered an "unknown high-frequency bat"). We mitigated this limitation, therefore, by exploring the data by call type and producing all bats, high-frequency and low-frequency models. However, it did occasionally compromise our ability to identify acoustic detections to the species level and our reporting on detections (Figure 2b) reflects this.

Ongoing research conducted by Aaron Aguirre, Dr. Matthew Mitchell and Dr. Kai Chan, as well as other members of M2L2 and the CHANS Lab at the University of British Columbia, may soon address some of the limitations of this research by mist-netting and acoustically detecting bats in parks throughout Vancouver, Burnaby, and Richmond, BC, as well as tracking bats to their roosts. Aaron's research will allow us to determine where bats are roosting in the area, how tightly-coupled bats are to their roost, and illuminate the factors that affect park habitats' ability to support bat foraging. Aaron and team should be able to address the broad questions: "which parks support abundant and diverse bat populations and why?" and "where are bats roosting in the area and why?". **This research should help to produce more specific recommendations for freshwater features, park design and connectivity, and roost characteristics to support bats.**

Lastly, research at the UBC Farm conducted by MSc student Daphne Chevalier, Dr. Juli Carillo, Dr. Matthew Mitchell, Dr. Quentin Geissmann, and Carly McGregor may help determine the influence of artificial light at night (ALAN) on flying insect, ground-dwelling arthropod, and bat activity. Their experiment will simulate different kinds of streetlights, including both "cooler" and "warmer" light wavelengths, and employ insect and arthropod traps and acoustic bat detectors to see which sorts of insects, arthropods, and bats the various lights attract or deter. **This research should help to produce specific recommendations regarding street light wavelengths to minimize their interactions with wildlife.**

Conclusion

Vancouver and Richmond, BC collectively host at least 10 species of bats in a relatively small geographical area. This amount of bat diversity may be attributed, in large part, to the 1) heterogeneous landscape (diversity of habitats in a small location, supporting bat species across varied ecological niches), and 2) the plasticity of some bat species (especially generalist bats, e.g., little and big brown bats) to use human-made habitats, habitat features (e.g., artificial freshwater bodies, built-structures as roosts), and consume a wide variety of insect species. Still, bats appear to avoid the most heavily populated, “gray” areas of the city (e.g., downtown, commercial areas) and instead, largely depend on green spaces with nearby freshwater (e.g., urban forests, cemeteries, golf courses, river edges, tree-lined paths). Green spaces and freshwater bodies capable of supporting high insect densities likely host the greatest abundance and diversity of bats.

Surprisingly, however, some bats were found along busy roads and in industrial areas. Yet, the same principles apply to these areas: bats are likely there to forage for insects, drink water, or roost. Roads offer convenient flight paths for foraging, especially for larger-bodied, low-frequency bats. Therefore, roads adjacent areas with high-insect densities (e.g., the roads surrounding and bisecting Pacific Spirit Park or Stanley Park) would create convenient insect-foraging opportunities near insect-generating habitat. Industrial areas may offer real foraging (weedy, unkempt vegetation and pooling water might support mosquitoes and other insects) and roosting (industrial equipment and storage facilities could make sheltered roosts) opportunities, or alternatively, are habitat sinks which attract bats from preferred habitat because of their open air-space, periods of quiet, and position relative to ideal habitat (e.g., nearby parks and golf courses) in South Vancouver but contain few of the resources bats need to survive, or some combination of both.

Vancouver’s civil servants have a host of plausible interventions to choose from to support more abundant and diverse bat populations, the ecological communities they rely on, and their benefits to people. Creating new bat-supporting habitats, like forests and ponds, would be most effective in bringing more bats to the city, but this type of intervention is rarely possible amidst other city priorities (e.g., housing). The next best option for bats is to improve the quality of existing habitats, especially the water quality of freshwater features and their surrounding areas and the native plant composition of forest and meadows. Riparian and other near-water vegetation are especially important in this regard, as they disproportionately contribute to bat foraging and hydration. Additionally, maintaining bat roosts (i.e., not evicting them when identified), including those identified in houses and older buildings, will help bats to cohabitate with humans in the city. Lastly, sensory pollutants, like light and noise, should be reduced or mitigated near bat supporting habitats - especially nearby freshwater and known roosts.

Healthy, diverse bat populations help to prevent the abundance of bothersome and disease-carrying mosquitoes and other insects and prevent losses to urban agriculture. By foraging for insects, bats have a cascading impact on an ecosystem. They limit insect consumption by other species, and change competitive dynamics between insect species, among a slew of other ecological impacts that likely help to maintain urban biodiversity. The presence of diverse bat species also reflects the health and diversity of our ecosystems, as they depend on diverse plant and insect communities and high water quality. They are unfairly stigmatized, and part of an effective campaign to support bats in Vancouver would necessarily involve education and public participation to help Vancouverites feel safe of bats and supportive of bats in our cities.

Acknowledgments

This research was made possible by internship funding provided by the UBC Ocean Leaders Program and the City of Vancouver awarded to Daniel Forrest, as well as an NSERC Master's fellowship awarded to Julia Craig. This work would not have occurred without the support of a large team, including Angela Danyluk, who supervised Daniel's internship, and Drs. Kai Chan and Matthew Mitchell, who supervise Daniel's graduate research and advised Daniel throughout this project. Kai was also Julia's master's supervisor and Matt served on her committee. Harold Eyster mentored and supported Daniel in constructing and mapping the statistical models, as well as editing this report. Joanne Fitzgibbons introduced Daniel to Angela Danyluk and Emily Dunlop, initiating this internship, advised Daniel in the project proposal, provided administrative support, and helped to interpret the results and edit this report. Dana Johnson supported Daniel in formulating this project, interpreting the results, and editing the text of this report. Emily Dunlop provided feedback on the project proposal and its relevance to the Vancouver Board of Parks and Recreation. Thank you all!

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Glossary

1. **Corridor**: an area of the city that can serve to facilitate bats' transit between hubs (typically parks and other primarily green spaces)
2. **Hotspot**: an area of the city that is likely to support diverse and abundant bat populations (defined as modeled cells with a predicted value greater than or equal to 0.75 out of 1 for likelihood of bat detection)
3. **Indicator Species** (or indicator taxonomic group): living organisms that are easily monitored and whose status reflects or predicts the condition(s) of the environment where they are found
4. **Functional Group**: species which tend to behave similarly, affect their environment similarly, and respond to similar environmental conditions, rather than share genetic similarity.

References

Barré, K., A. Vernet, C. Azam, I. Le Viol, A. Dumont, T. Deana, S. Vincent, S. Challéat, and C. Kerbiriou. 2022. Landscape composition drives the impacts of artificial light at night on insectivorous bats. Environmental Pollution 292:118394.

Bennett, V. J., and A. A. Zurcher. 2013. When corridors collide: Road-related disturbance in commuting bats: Disturbance of Bats by Vehicles. The Journal of Wildlife Management 77:93–101.

Bunkley, J. P., C. J. W. McClure, A. Y. Kawahara, C. D. Francis, and J. R. Barber. 2017. Anthropogenic noise changes arthropod abundances. Ecology and Evolution 7:2977–2985.

CBC News. 2023, April 3. Deadly fungus that has wiped out bat populations detected in B.C. | CBC News. https://www.cbc.ca/news/canada/british-columbia/bc-bats-white-nose-syndrome-1.6800262.

Craig, J., M. Sarell, and S. Holroyd. 2014. Got Bats? BC Community Bat Project Frequency

Asked Questions. Prepared for the BC Community Bat Project Initiative.

Cravens, Z. M., V. A. Brown, T. J. Divoll, and J. G. Boyles. 2018. Illuminating prey selection in an insectivorous bat community exposed to artificial light at night. Journal of Applied Ecology 55:705–713.

Denzinger, A., and H.-U. Schnitzler. 2013. Bat guilds, a concept to classify the highly diverse foraging and echolocation behaviors of microchiropteran bats. Frontiers in Physiology 4.

Dixon, M. D. 2012. Relationship between land cover and insectivorous bat activity in an urban landscape. Urban Ecosystems 15:683–695.

Finch, D., H. Schofield, and F. Mathews. 2020. Traffic noise playback reduces the activity and feeding behaviour of free-living bats. Environmental Pollution 263:114405.

Fukui, D., M. Murakami, S. Nakano, and T. Aoi. 2006. Effect of emergent aquatic insects on bat foraging in a riparian forest. Journal of Animal Ecology 75:1252–1258.

Fure, A. 2012. Bats and lighting–six years on. London Naturalist 91:69–88.

Gaston, K. J., T. W. Davies, J. Bennie, and J. Hopkins. 2012. REVIEW: Reducing the ecological consequences of night-time light pollution: options and developments. Journal of Applied Ecology 49:1256–1266.

Kolkert, H., R. Andrew, R. Smith, R. Rader, and N. Reid. 2020. Insectivorous bats selectively source moths and eat mostly pest insects on dryland and irrigated cotton farms. Ecology and Evolution 10:371–388.

Krauel, J. J., and G. LeBuhn. 2016. Patterns of Bat Distribution and Foraging Activity in a Highly Urbanized Temperate Environment. PLOS ONE 11:e0168927.

Kunz, T. H. 1982. Roosting Ecology of Bats. Pages 1–55 *in* T. H. Kunz, editor. Ecology of Bats. Springer US, Boston, MA.

Kunz, T. H., and M. B. Fenton, editors. 2005. Bat ecology. Paperback edition. University of Chicago Press, Chicago, Ill.

Kunz, T. H., L. F. Lumsden, and M. Fenton. 2003. Ecology of cavity and foliage roosting bats.

Bat ecology 1:3–89.

Lehrer, E. W., T. Gallo, M. Fidino, R. J. Kilgour, P. J. Wolff, and S. B. Magle. 2021. Urban bat occupancy is highly influenced by noise and the location of water: Considerations for nature-based urban planning. Landscape and Urban Planning 210:104063.

Li, H., and K. T. Wilkins. 2022. Predator-Prey Relationship between Urban Bats and Insects Impacted by Both Artificial Light at Night and Spatial Clutter. Biology 11:829.

Longcore, T., H. L. Aldern, J. F. Eggers, S. Flores, L. Franco, E. Hirshfield-Yamanishi, L. N. Petrinec, W. A. Yan, and A. M. Barroso. 2015. Tuning the white light spectrum of light emitting diode lamps to reduce attraction of nocturnal arthropods. Philosophical Transactions of the Royal Society B: Biological Sciences 370:20140125.

Luck, G. W., L. Smallbone, C. Threlfall, and B. Law. 2013. Patterns in bat functional guilds across multiple urban centres in south-eastern Australia. Landscape Ecology 28:455–469.

Luo, J., B. M. Siemers, and K. Koselj. 2015. How anthropogenic noise affects foraging. Global Change Biology 21:3278–3289.

Moretto, L., and C. M. Francis. 2017. What factors limit bat abundance and diversity in temperate, North American urban environments? Journal of Urban Ecology 3.

Nakamoto, A., K. Kinjo, and M. Izawa. 2007. Food habits of Orii's flying-fox, Pteropus dasymallus inopinatus, in relation to food availability in an urban area of Okinawa-jima Island, the Ryukyu Archipelago, Japan. Acta Chiropterologica 9:237–249.

Neuweiler, G. 1984. Foraging, echolocation and audition in bats. Naturwissenschaften 71:446–455.

Norberg, U. M., and J. M. V. Rayner. 1987. Ecological morphology and flight in bats (Mammalia; Chiroptera): wing adaptations, flight performance, foraging strategy and echolocation. Philosophical Transactions of the Royal Society of London. B, Biological Sciences 316:335–427.

Nunn, J. 2007, May 13. Water for Wildlife. BATS Magazine, Bat Conservation International 25.

Parris, K. M., M. Amati, S. A. Bekessy, D. Dagenais, O. Fryd, A. K. Hahs, D. Hes, S. J. Imberger, S. J. Livesley, A. J. Marshall, J. R. Rhodes, C. G. Threlfall, R. Tingley, R. van der Ree, C. J. Walsh, M. L. Wilkerson, and N. S. G. Williams. 2018. The seven lamps of planning for biodiversity in the city. Cities 83:44–53.

Rowse, E., D. Lewanzik, E. Stone, S. Harris, and G. Jones. 2016. Dark matters: the effects of artificial lighting on bats. Bats in the Anthropocene: Conservation of bats in a changing world:187–213.

Russo, D., and L. Ancillotto. 2015. Sensitivity of bats to urbanization: a review. Mammalian Biology 80:205–212.

Schnitzler, H.-U., and E. K. V. Kalko. 2001. Echolocation by Insect-Eating Bats. BioScience 51:557.

Shannon, G., M. F. McKenna, L. M. Angeloni, K. R. Crooks, K. M. Fristrup, E. Brown, K. A. Warner, M. D. Nelson, C. White, J. Briggs, S. McFarland, and G. Wittemyer. 2016. A synthesis of two decades of research documenting the effects of noise on wildlife: Effects of anthropogenic noise on wildlife. Biological Reviews 91:982–1005.

Stawski, C., C. K. R. Willis, and F. Geiser. 2014. The importance of temporal heterothermy in bats. Journal of Zoology 292:86–100.

Stone, E. L., S. Harris, and G. Jones. 2015. Impacts of artificial lighting on bats: a review of challenges and solutions. Mammalian Biology 80:213–219.

Straka, T. M., P. E. Lentini, L. F. Lumsden, S. Buchholz, B. A. Wintle, and R. van der Ree. 2020. Clean and Green Urban Water Bodies Benefit Nocturnal Flying Insects and Their Predators, Insectivorous Bats. Sustainability 12:2634.

Straka, T. M., P. E. Lentini, L. F. Lumsden, B. A. Wintle, and R. Ree. 2016. Urban bat communities are affected by wetland size, quality, and pollution levels. Ecology and Evolution 6:4761–4774.

Suarez-Rubio, M., C. Ille, and A. Bruckner. 2018. Insectivorous bats respond to vegetation complexity in urban green spaces. Ecology and Evolution 8:3240–3253.

The City of Vancouver. 2022. The Vancouver Plan. The City of Vancouver, Vancouver, BC, Canada.

Threlfall, C. G., B. Law, and P. B. Banks. 2012. Sensitivity of insectivorous bats to urbanization: Implications for suburban conservation planning. Biological Conservation 146:41–52.

Threlfall, C. G., N. S. G. Williams, A. K. Hahs, and S. J. Livesley. 2016. Approaches to urban vegetation management and the impacts on urban bird and bat assemblages. Landscape and Urban Planning 153:28–39.

Wolf, J. M., J. M. Jeschke, C. C. Voigt, and Y. Itescu. 2022. Urban affinity and its associated traits: A global analysis of bats. Global Change Biology 28:5667–5682.

Wu, Y., S. G. DuBay, R. K. Colwell, J. Ran, and F. Lei. 2017. Mobile hotspots and refugia of avian diversity in the mountains of south-west China under past and contemporary global climate change. Journal of Biogeography 44:615–626.

Yantén, A. V., A. Cruz-Roa, and F. A. Sánchez. 2022. Traffic noise affects foraging behavior and echolocation in the Lesser Bulldog Bat, Noctilio albiventris (Chiroptera: Noctilionidae). Behavioural Processes 203:104775.

Appendix

Table A1. (Adapted from Julia Craig's master's thesis, UBC, 2022). Sources of all GIS data, manual adjustments made, and the analyses performed in ArcGIS Pro.

Data	**Data Type**	**Date**	**Source**	**Manual Adjustsments**	**Analyses Performed**
Land use	Vector	2016	MetroVancouver (https://open-data-portal-metrovancouver.hub.arcgis.com/datasets/28de9170a9434974bffc24c119261310_1/about)	1. Collated all classes into 10 appropriate groups 2. Deleted all sidewalks 3. Merged with freshwater layer	1. 10 class groups: Sea, River, Freshwater, Urban, Open park (all parks that are open, golf courses, airport), Forested park, Residential, Industrial, Farmland and Road 2. Calculated the area and percentage of each land use class per buffer.
Road type	Vector	2022	OpenStreetMap (http://download.geofabrik.de/north-america/canada/british-columbia.html)	Collated all classes into 4 groups (unpaved path, no/low traffic road, residential road, and urban road)	1. Calculated the length and percentage of each road type per buffer 2. Coerced classes to a weighted continuous variable of traffic where percentage of each road type was multiplied by a weighted value based on its relative traffic (0 * unpaved path, 3 * no/low traffic road, 9 * residential road, and 27 * urban road)
Greenness	Vector	2017	Landsat 8, Google Earth Engine (https://code.earthengine.google.com/?scriptPath=Exam	None	1. Calculated NDVI with google earth engine for both cities 2. Converted raster

			ples%3ADatasets%2FLANDSAT_LE07_C01_T1_ANNUAL_GREENEST_TOA)		into vector 3. Calculated the area of and percentage greenness per buffer.
Tall Vegetation	Raster	2018, 2019	City of Vancouver (https://opendata.vancouver.ca/explore/dataset/lidar-2018/information/) Richmond (https://glad.umd.edu/dataset/gedi)	1. Removed any vegetation under 3m in the Richmond file	1. Converted raster into vector 2. Isolated for tall vegetation class 3. Calculated the area and percentage of tall vegetation per buffer.
Buildings	Vector	2022	OpenStreetMap (http://download.geofabrik.de/north-america/canada/british-columbia.html)	None	1. Calculated the area and percentage of buildings per buffer.
Light Pollution	Raster	2013	NASA, retrieved through Wikipedia (https://spaceflight.nasa.gov/gallery/images/station/crew-35/html/iss035e013076.html) (https://commons.wikimedia.org/wiki/File:ISS-35_Night_image_of_Vancouver,_British_Columbia,_Canada.jpg)	A portion of Richmond was out of frame, so using “pixel editor” and comparing to other night photos, Julia graphed an equally bright neighbourhood over the missing potion	1. Calculated the average light pollution within each buffer, where 0 = completely black (no light) and 255 = completely white (maximum brightness) 2. The average brightness was calculated for each buffer.
Freshwater	Vector	2022	British Columbia Data Catalogue (https://catalogue.data.gov.bc.ca/dataset/bc-water-polygons-1-6-000-000-digital-baseline-mapping)	Manually added polygons for smaller pools, ponds, rivers, streams and water features that were visible in aerial photos from Planet.com and Google maps.	1. Distance to nearest freshwater source was calculated for each segment 2. Combined with land use layer.

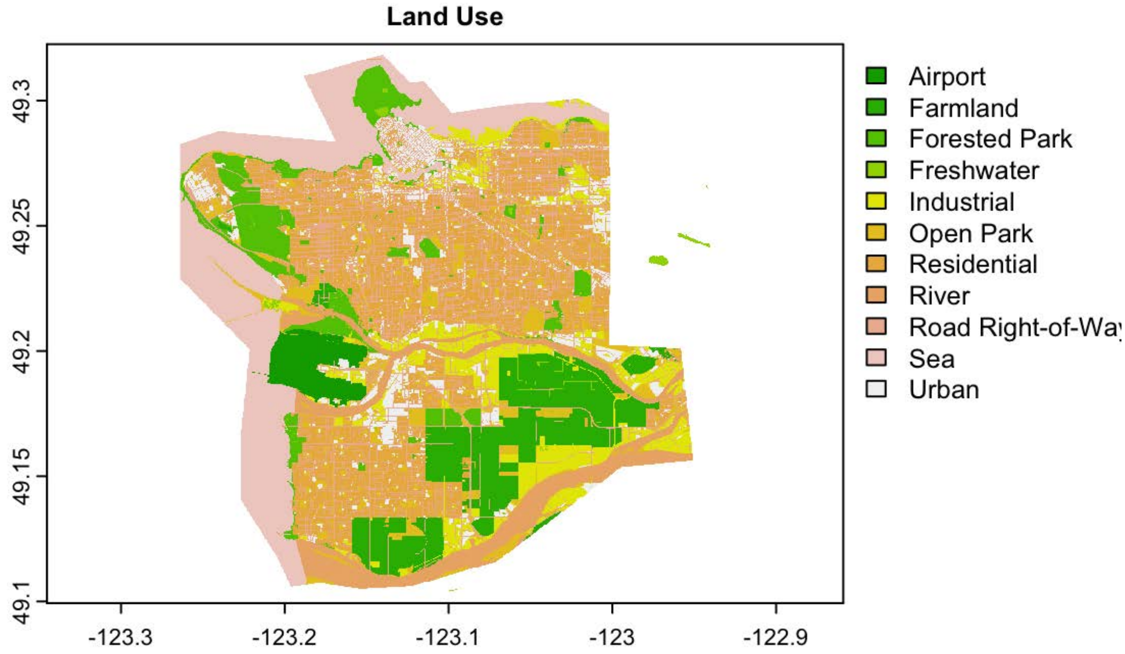

Figure A1. Map of land use classifications raster used as input for model predictions.

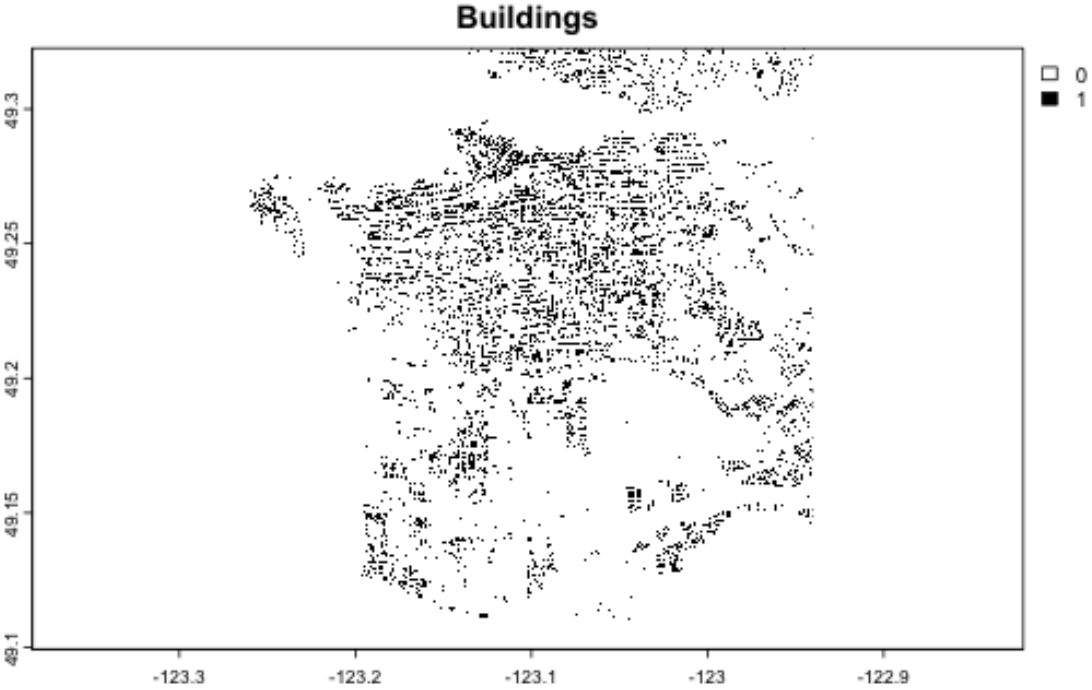

Figure A2. Map of buildings raster used as input for model predictions.

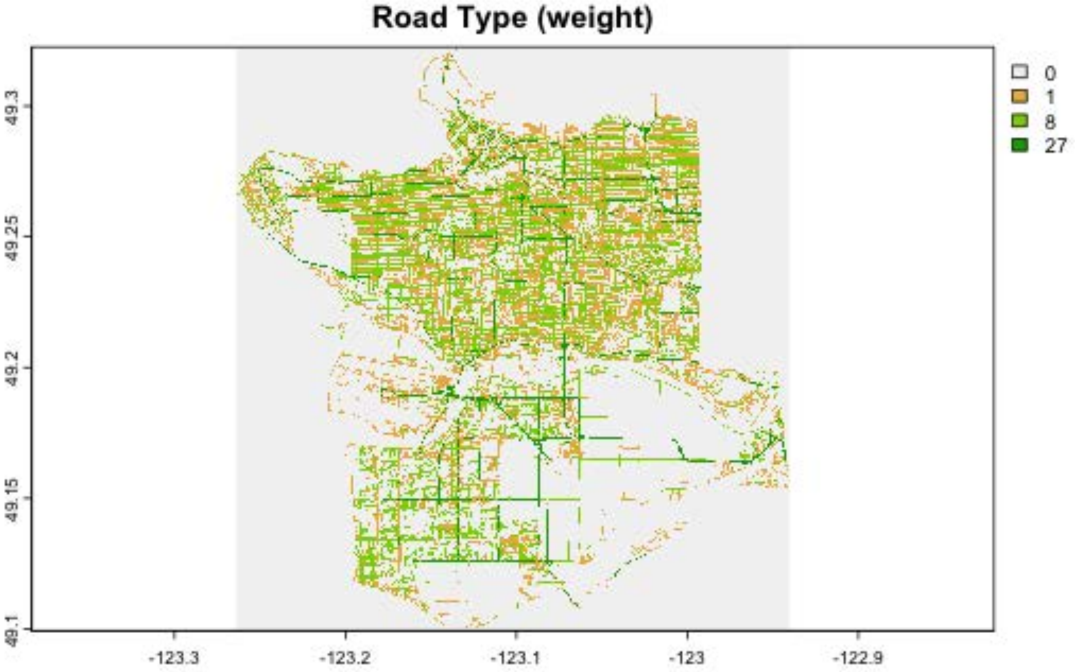

Figure A3. Map of weighted road type raster used as input for model predictions. No or low traffic = 0, laneways and paths = 1, residential roads = 8, and high traffic (highways, commercial, etc.) = 27.

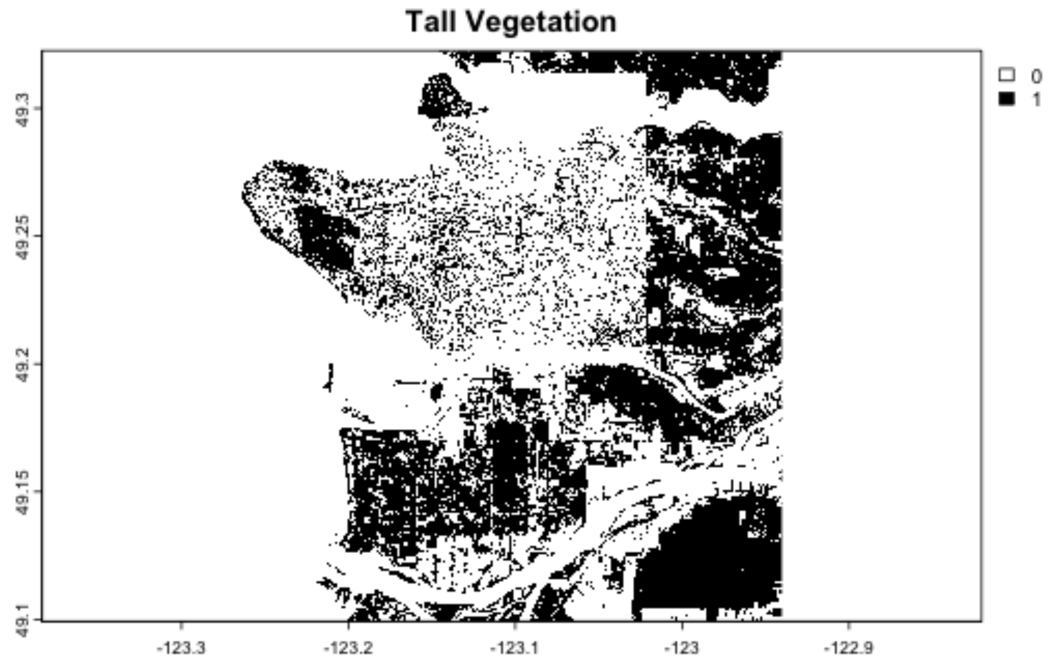

Figure A4. Map of tall vegetation (>3 m. height) raster used as input for model predictions.

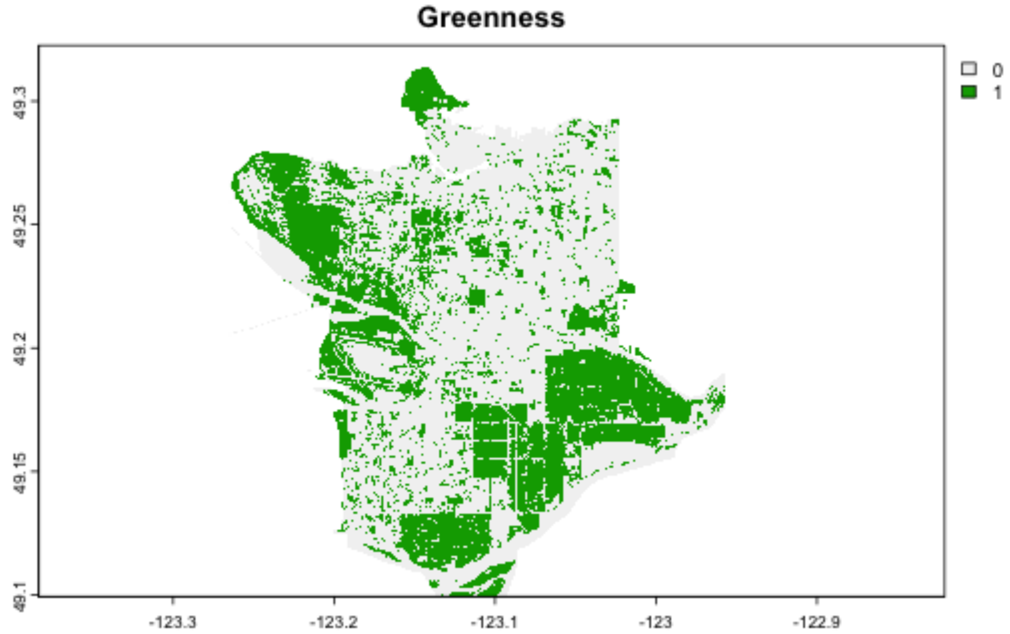

Figure A5. Map of greenness raster used as input for model predictions. Values of 0 are land areas that are not green and values of 1 are land areas that are green.

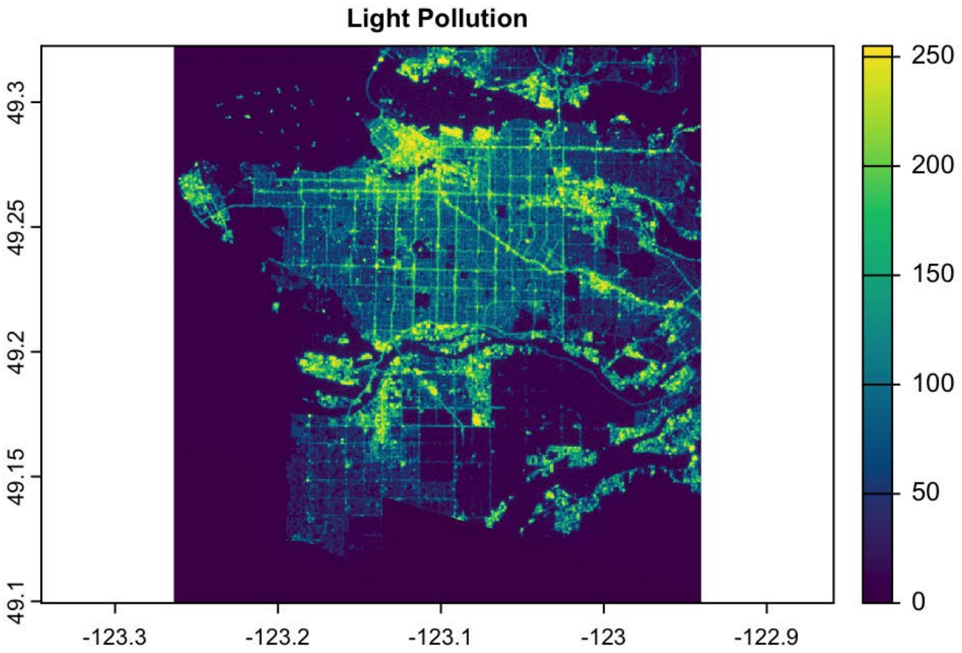

Figure A6. Map of light pollution raster used as input for model predictions. Areas with values near 0 are nearly devoid of light and areas with values near 250 are near maximum brightness (fully white in the image).

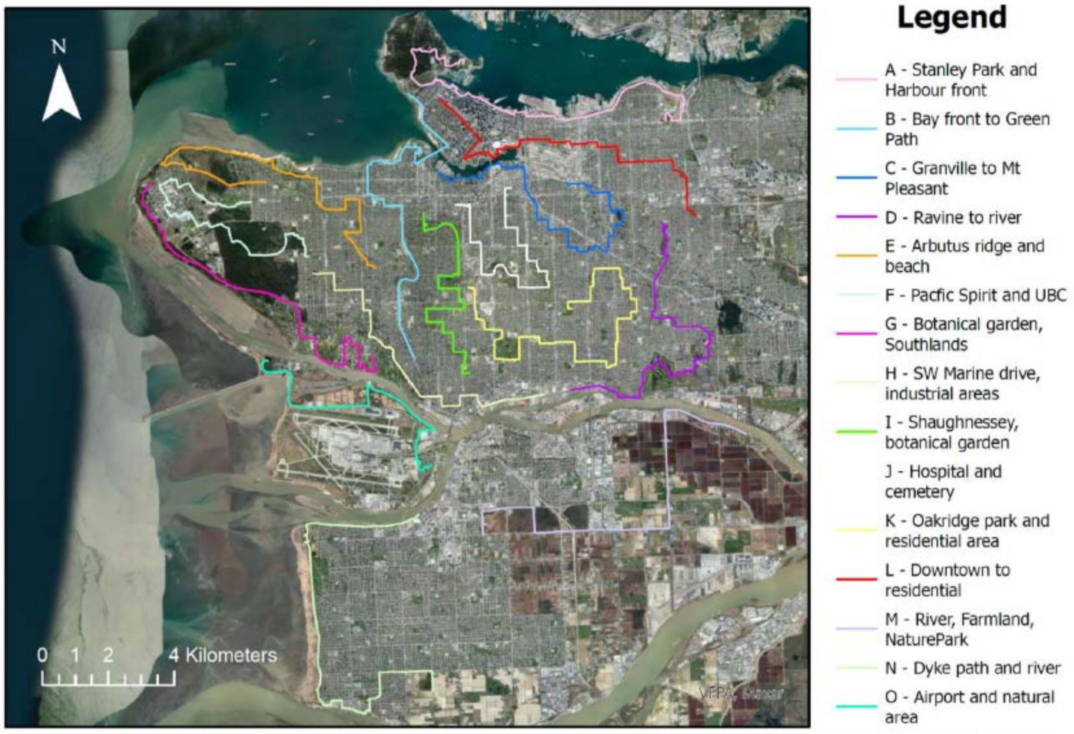

Figure A7. Map of 15 bicycle transects across Vancouver and Richmond, BC acoustically surveyed for bats by Julia Craig in Summer 2021. Basemap: Earthstar Geographics.

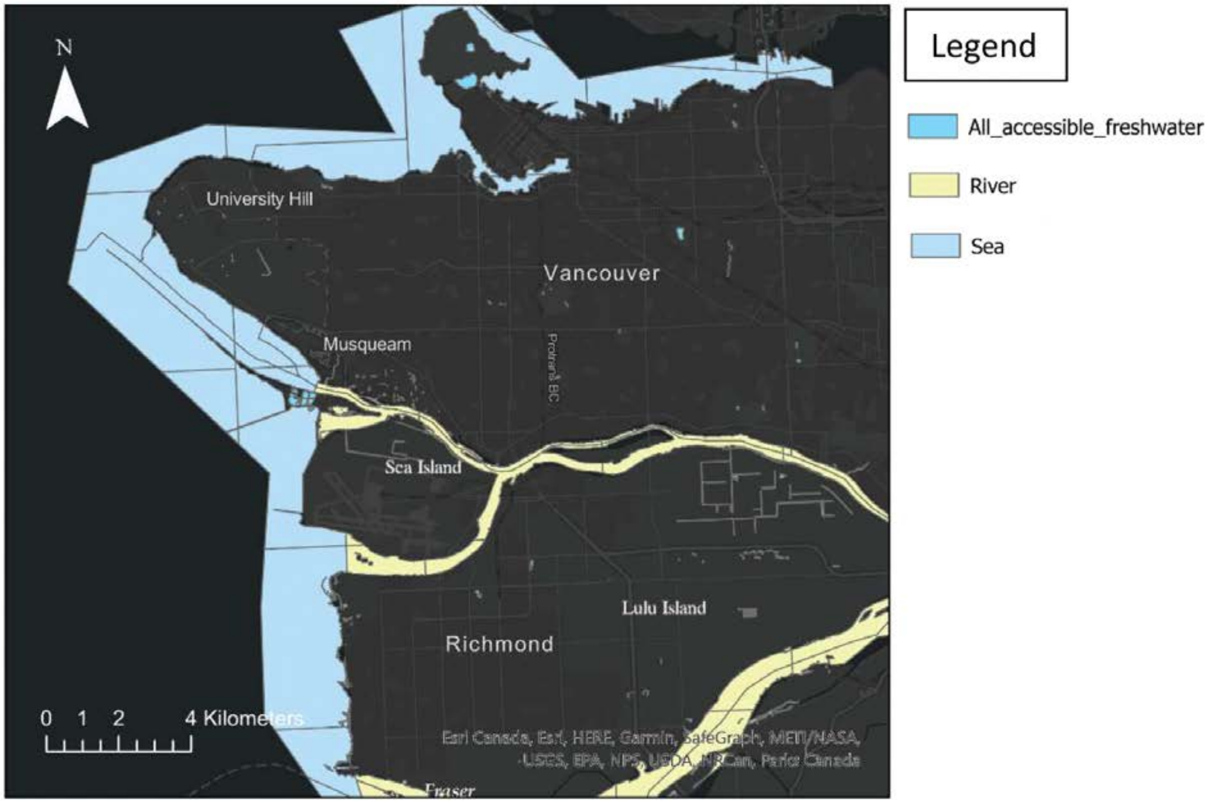

Figure A8. Map of water features across the survey area. Freshwater features in deep aqua (most are small and hard to see with the naked eye; see Lost Lagoon and Beaver Lake in Stanley Park – top of map – for visible examples), river in pale yellow, ocean water in sky blue.

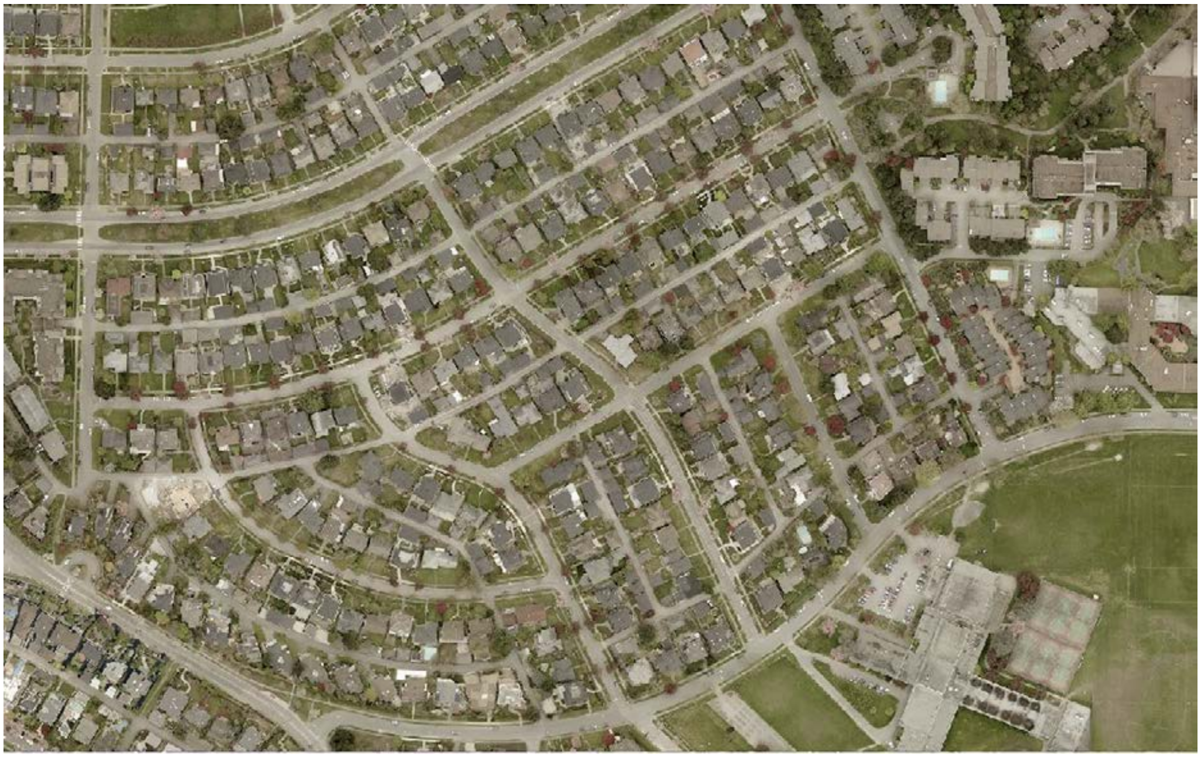

Figure A9. Residential. Orthophoto of a residential area, Arbutus Ridge, in Vancouver, BC. Obtained from the City of Vancouver’s OpenData Portal.

Figure A10. Farmland. Orthophoto of agricultural lands in Northeast Richmond obtained via the City of Vancouver’s OpenData Portal.