Birds in Suburbs:
Altering Habitat, Species Assemblages, & Science Communication

Jack Henry DeLap

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Reading Committee:

John Marzluff, Chair

Marc Miller

Sarah Converse

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Abstract

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Jack Henry DeLap

Chair of the Supervisory Committee:
Professor John M. Marzluff
School of Environmental & Forest Sciences

Human modification of the environment rapidly alters ecological processes and the composition of plant and animal communities. Understanding the impacts of such anthropogenic disturbances are needed to predict future biotic conditions, inform land management practices, and conserve biological diversity. This dissertation aimed to generate original scientific research on anthropogenic disturbance ecology and present those findings to a broad audience.

I had five specific objectives and associated findings. First, to assess over a decade of landscape change (1998-2010) occurring in the Puget Lowlands of Washington state, where exurban areas are converting from forest to either low-density conservation development (CD) or higher density planned community development (PCD). Second, to test predictions of successional change (stability, heterogeneity, and diversity) in structuring local bird communities of these emerging suburbs. Third, to quantify abundance of birds in each form of development by both tolerance of human activity (synanthropic guilds) and individual species persistence. Fourth, to extend the reach of informal education by designing a public science exhibition format. Fifth, to communicate suburban-bird ecology to a broader literary audience through original illustrations. Applying object-oriented image assessment (OBIA) and compositional analyses to available orthophotography, I found the rate of land conversion, amount of built cover, and forest loss positively correlated with housing density. However, habitat fragmentation (total edge) increased equally in CDs and PCDs. As predicted by classical succession, bird communities following disturbance became more stable over time, less heterogeneous, and grew in diversity. However, CDs stabilized more quickly and remained more heterogeneous than PCDs. CDs retained more native forest birds (avoiders), excluded more synanthropic (exploiter) species, and hosted similar numbers of early successional (adaptor) species relative to PCDs; however, a few highly abundant species dominated each guild. I propose the Living Science Journal (LSJ), an interactive museum-style exhibition format to feature peer-reviewed ecological studies for informal public education. Finally, I created 41original natural science illustrations to accompany the book *Welcome to Subirdia: Sharing our neighborhoods with wrens, robins, woodpeckers, and other wildlife,* authored by my doctoral advisor, Professor John Marzluff.

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DEDICATION

I dedicate this dissertation to Paul Krapfel. Paul was the naturalist and science teacher at The Farm School, an experimental elementary educational institution administered by the University of California, Irvine. A former Park Ranger at Mesa Verde National Park, Paul taught me a great deal about curiosity and observation of the natural world. Paul guided my early interest in zoology by identifying snakes and lizards at schoolyard recess, waterbirds in the local wetlands, and searching for Red-winged blackbird nests in the nearby mustard fields. He nurtured my growing interest in ecology with long discussions and curated readings from Aldo Leopold (Sand County Almanac) and his self-published examination, *Shifting*, of James Lovelock's Gaia Hypothesis. Thank you, Paul. I am eternally grateful.

Chapter 1. INTRODUCTION

1.1 OVERVIEW

In this dissertation, I investigate bird abundances during and after subdivision construction and seek to apply my ecological discoveries to a broad audience through academic (research articles), informal experiential learning (proposed public science exhibition design) and integrating art and science (ecological concept illustrations) in popular non-fiction literature.

Beyond this introductory chapter, I present four original works.

Chapter 2 focuses on the land conversion from forest to new residential suburbs and the nature of community succession in bird communities (stability, heterogeneity, diversity) impacted by this type of anthropogenic disturbance in the Central Puget Lowlands of Washington state, intended for publication in a professional ecological science journal.

Chapter 3 builds upon the work of Chapter 2, evaluating the response of bird populations (relative abundance) to suburban development at the level of both human tolerance guilds and individual species. Also intended for publication in the ecological science literature, the implications of this chapter include land use planning and avian conservation of newly developing lands.

Chapter 4 concentrates on the communication of science beyond professional and academic audiences. I propose a museum-style interactive exhibit design drawing inspiration from the scientific method, natural history dioramas, and participatory citizen science, beginning with a brief discussion of information theory and contemporary cultural and educational challenges to successfully sharing science understanding.

Chapter 5 presents a collection of my original natural science illustrations (41 in total), designed to aid the education of a lay audience on urban bird research insights featured in Welcome to Subirdia: Sharing our neighborhoods with wrens, robins, woodpeckers, and other wildlife (Marzluff 2015).

1.2 BACKGROUND & RELEVANCE

1.2.1 *Population Growth & Settlement Expansion*

Human population growth and the commensurate rise in settlement, agriculture, resource extraction, energy consumption, and waste production have led to profound global land cover and land use changes (Meyer and Turner 1992, Vitousek 1992, 1994, Seto et al. 2011). Changes in land cover and land use (agriculture and urbanization together) are the greatest imminent threat to biodiversity (Maxwell et al. 2016), altering, degrading, or entirely losing essential existing habitat (Wilson 1992, Fischer and Lindenmayer 2007). Land cover and land use change in the form of settlement or human construction for habitation, industry, and transportation (Meyer and Turner 1992), can vary in intensity and extent (Theobald 2001, Foley et al. 2005, Grimm et al. 2008, Marzluff et al. 2008, Pickett et al. 2011, Bai et al. 2017). Urbanization of forest lands, or the conversion of existing forest to a mosaic of suburban development and relictual forest patches or vegetation fragments, is typical in the Pacific Northwest of the United States.

In the Seattle metropolitan region of Washington State, generalized urbanization and suburban development specifically are on the rise (Robinson et al. 2005). New development outside the urban core (beyond the urban growth boundary) and settlement expansion occurs twice as fast as inside the urban center. Suburban developments occupy an intermediate range of settlement density, where human dwellings share the landscape with scattered 'green spaces,' creating a landscape mosaic of 'perforated' forest (Marzluff et al. 2001). These vegetated fragments may be composed exclusively of native habitat, introduced grasses, ornamental trees and shrubs, or a mixture.

1.2.2 *Breeding Bird Communities in Residential Settlements*

Local breeding bird communities, composed of both resident and migratory species, are an excellent indicator for measuring ecosystem function and biodiversity in the face of such changing human-dominated landscapes (Marzluff et al. 2001, Melles et al. 2003a, Crooks et al. 2004, Donnelly and Marzluff 2004, Blewett and Marzluff 2005, Hansen et al. 2005b, Hostetler et al. 2005, Devictor et al. 2007, Marzluff et al. 2007, Whittaker and Marzluff 2009).

1.2.3 *Ecological Succession Theory*

Community Succession (Clements 1916b), or the progressive change in plant (and animal) communities following natural disturbances, is considered a foundational concept in the field of ecology (Connell and Slatyer 1977, Pickett et al. 1987, Ford and Ishii 2001, Pickett et al. 2009, Miller and Terhorst 2012). In devising community assembly rules (Diamond and Gilpin 1980), a theoretical outgrowth of ecological succession, random events do not determine local community assemblages. Instead, species interactions, specifically competition, is thought to structure communities, leading to decades of scientific debate (Diamond et al. 1976, Simberloff 1976, Connor and Simberloff 1979, Gilpin and Diamond 1981, Simberloff and Connor 1981, Gilpin and Diamond 1982) (for review see Wiens, 1989). This body of research has recently been revisited (Gotelli and McCabe 2002, Ulrich 2004) in both avian and non-avian systems (Jackson et al. 1992, Burns 2008). Wiens (1989) stated that evidence to support this theory must move beyond merely describing species patterns in existing locations; inferring habitat manipulation is critical to demonstrating any 'nonrandom' practices.

1.2.4 *Residential Growth Management & Avian Conservation*

Managing the expansion of human settlement to maintain avian biodiversity is increasingly challenging. Suburbs support higher diversity than many of their most urban counterparts (Blair 1996, Mckinney 2006, Pickett et al. 2011); however, not all subdivisions are equal. Do residential communities of people and birds best coexist by allocating dense housing accompanied by minimally disturbed native habitat patches or locating dwellings in a more dispersed arrangement through exurban areas (Geschke et al. 2018)? Evaluating multiple forms of development for their short- and long-term influence can help instruct residential planning for maximizing native birds.

1.2.5 *Science Communication & Resurgence of Science-Art Integration (Sci-Art)*

Research scientists must produce rigorous original work and share their findings if their efforts are to contribute to increased knowledge and improved decision-making. Communication theory (Craig 1999), such as the work of pioneering information theorists

Claude Shannon and Warren Weaver (Shannon and Weaver 1949), provides a helpful frame to evaluate the strengths and weaknesses of the current science-information landscape. Scientific research primarily disseminates through publication in peer-reviewed scientific literature, where professional and academic scientists are the intended audience. From this source, information is summarized, re-packaged, and transmitted by non-scientists for consumption by the public via popular media and journalistic outlets. Scientists increasingly engage the broader public (Besley et al. 2013). Natural history museums represent one of the few, if not the only, models of a physical site for the public to view and potentially interact with evidence-based knowledge concerning the natural world. However, natural history museums, by definition, tend to focus their exhibitions on organismal life history and human culture, typically displayed as collections of authoritatively curated facts. The coarse and fine-scale ecosystem level relationships and the fundamental process of scientific inquiry that produces and interprets the resulting information are missing from such presentations. The incremental progression of scientific understanding, building on previous work, often only to retrace, mend or repair past paradigms of knowledge, is largely missing in public exhibitions. Sci-arts, or the integration of science with various forms of artistic expression, is gaining in popularity (Parks and White 2021, Stengler 2021, Trickett 2021) as an alternate channel to meet the societal need for elevating public scientific literacy and engagement. Visual imagery accompanying popular science literature, such as books (Isakhanli 2019) and comic books (Friesen et al. 2018), can activate the imagination and engagement of a broad demographic.

1.2.6 *Research Objectives*

My first objective is to quantify and qualify landscape change in the form of deforestation and subsequent new residential development in the Central Puget Lowlands near Seattle, Washington. How does the composition, the type, and amount of landcover, change through time in conservation (low density) and planned community (high density) developments relative to nearby forest reserves and pre-existing suburbs? Is the pace of land conversion similar or different among the two subdivision types?

Secondly, I aim to test predictions for community succession using bird assemblages inhabiting these shifting landscapes. Are bird assemblages in these emerging subdivisions more chaotic than in nearby intact forests or suburbs? While the vegetative characteristics of this anthropogenic disturbance differ from classical secondary succession, are the temporal changes in faunal community stability (increasing), heterogeneity (decreasing), and diversity (increasing) still as expected?

Thirdly, I assess the relative impact of conservation (low housing density) and master-planned community (higher housing density) suburban development on breeding bird abundances (guilds and species). Using synanthropic guilds (tolerance to human conditions) as a response measure, are avoiders (native forest species), adaptors (native generalist species), or exploiters (native and non-native human commensal species) differentially represented across the two types of residential development? How representative is the overall response of these commonly applied guilds to the individual species represented within each? What, if any, are the implications of influencing future bird communities through residential planning of these two forms of subdivisions?

For my fourth objective, I develop a proposal design for public science exhibition to share research findings directly with the public. Inspired by museum habitat dioramas, I advocate using digital images, text, and sound projected into a modest-sized viewing area for an in-person experience. The resulting display design will serve as the prototype of a physical science periodical, emphasizing the scientific process, public engagement, and skills in interpreting experimental results.

For my fifth and last objective, I produce a series of original artwork as hand-rendered and digitally composed illustrations (stylus on tablet, graphic software) to communicate urban ecological concepts for a book project authored by my dissertation advisor. Here I apply my skills and experience as an artist/illustrator/ background (B.A. Fine Art, UW coursework in Scientific Illustration, professional website, and graphic designer) to showcase ecological concepts using symbolic imagery to clarify and reinforce ecological insights.

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Chapter 2. ARRESTED DEVELOPMENT: SUCCESSIONAL PATHWAYS OF SUBURBAN BIRD COMMUNITIES

2.1 ABSTRACT

As human population growth and changing settlement patterns drive the expansion of residential development in peri-urban lands, we need a greater understanding of how these converting landscapes progress and impact local ecologies. Rarely tested are the potential successional responses of animal communities to these anthropogenic stresses. We assess over a decade of landscape change as secondary forests are converted to residential subdivisions in the Seattle metropolitan area of Washington State and evaluate affected local breeding bird communities for key successional patterns (stability, heterogeneity, diversity). Forest loss, fragmentation, and the introduction of built land cover substantially disrupted species assemblages relative to both forested controls and nearby pre-existing suburbs. Affected avian communities gained stability and diversity over time, though with decreased heterogeneity. We propose an alternative pathway (to secondary succession) for avian communities occupying these human-modified systems. Tertiary succession can describe areas partially fixed by built landcover while retaining significant native habitat. Depending on future conditions, bird assemblages may achieve 1) alternate stable states without further habitat modification, 2) experience ecological release in settings returning to variable pre-subdivision conditions, or 3) transcend successional processes altogether should environments continue to transform unpredictably.

2.2 KEYWORDS

Landcover change, urban birds, community succession, stability, heterogeneity, diversity, subdivision, suburban development, guild, Seattle, Washington State

2.3 INTRODUCTION

Human alteration of landscapes is at an all-time high (Foley et al. 2005, Ellis 2021), with global urbanization a critical driving force (Grimm et al. 2008, Creutzig et al. 2019). Many urban centers partially absorb population growth through infill (York et al. 2011) and vertical development (Lin et al. 2014). However, conversion of exurban lands, or "sprawl," extends the built environment into areas historically allocated for agriculture, commercial timber production, or less modified native vegetation (Irwin and Bockstael 2007). The various impacts of such anthropogenic disturbance are increasingly a focus of ecological research (Alberti 2005, Shochat et al. 2006, Pickett et al. 2011), including the measurable disruption to wildlife communities inhabiting these transforming lands (Mckinney 2002, Hansen et al. 2005a, Hansen et al. 2005b, Fischer and Lindenmayer 2007, Grimm et al. 2008, Lepczyk et al. 2008, Marzluff et al. 2008, Pickett et al. 2011, Magle et al. 2012, Lowry et al. 2013, Rodewald et al. 2013, Aronson et al. 2014, Beninde et al. 2015, Pejchar et al. 2015, Lepczyk et al. 2017, Marzluff 2017). Understanding the processes responsible for structuring animal communities is critical in the wake of anthropogenic land conversion. One key to increasing our ecological understanding and predicting future biological conditions may be testing for successional change in breeding bird communities.

The theory of ecological succession has a long history (Clements 1916a, Gleason 1939), with waxing and waning interest in the concept's explanatory power (Pickett et al. 2009).

Succession was initially conceived to explain the compositional progression of vegetative communities in newly established areas such as emergent islands or volcanic eruptions (primary succession) or places recovering from (incomplete) natural disturbances (secondary succession), such as windthrow, floods, or fire (Paine et al. 1998). Community assembly predictions extended the successional model to longitudinal change in animal communities, namely birds, an often-debated application (Diamond 1975, Connor and Simberloff 1979, Keddy 1992, Austin 1999, Belyea and Lancaster 1999, Ulrich 2004).

Ecological succession theory has been applied in various contexts using ecological gradient analysis (Ter Braak and Prentice 1988), including the study of avian communities in urbanizing lands (Blair 1996). Residential development does not follow the classical succession model, however, as landcover converts to a mosaic of residential, commercial, and relictual green spaces held in either artificial stasis or disequilibrium (Rebele 1994), never progressing to a "climax community" of purely native late seral flora and fauna. Nonetheless, metrics used to assess successional processes (Pickett et al. 1987) may well apply to the alternate states of urbanization (Connell and Slatyer 1977). For instance, detecting directional changes in the (1) stability, (2) heterogeneity, and (3) diversity of ecological communities (Miller and Terhorst 2012) experiencing anthropogenic landscape change may both improve ecological understanding and assist in predicting community responses to conservation strategies.

Exurban development in western Washington State, USA, exacerbated by regional urbanization (Hepinstall et al. 2008), led to extensive deforestation in the last quarter of the 21st century (Robinson et al. 2005) and was expected to continue through at least 2020 (Kline et al. 2009). In 1998, researchers initiated a long-term investigation of urbanization impacts on birds of the Central Puget Sound region (Blewett and Marzluff 2005, Farwell and Marzluff 2013, Marzluff et al. 2015). Here we use a subset of the resulting data to contrast landscape and avian responses through time at sites undergoing conversion from forest to residential development with existing suburbs and forest reserves. We studied two forms of active development: conservation developments and planned community developments, hereafter CDs and PCDs. CDs contain less overall built cover than PCDs, e.g., lower density housing, with residences often clustered alongside native habitat, though residences can be more diffuse (Feinberg et al. 2015). PCDs, or master-planned communities, have higher-density residential blocks. This diversity in development types allowed us to evaluate real-time impacts of landscape change on avian community composition and potentially complement insights from the urbanization-gradient approach (Blair 1996, Mcdonnell et al. 1997, Melles et al. 2003a, Crooks et al. 2004, Chace and Walsh 2006, Mckinney 2006, Palomino and Carrascal 2007, Marzluff et al. 2008, Van Rensburg et al. 2009).

Our objective was to investigate how urbanization processes (longitudinal as opposed to "space-for-time" gradient analysis) modify landcover and avian communities. Specifically, we hypothesized that urban development proceeds similarly to ecological succession, most likely culminating in an alternative stable state instead of a single climax community (Donnelly and Marzluff 2004, Tilt and Cerveny 2013, Feinberg et al. 2015). We developed four predictions. First, CDs should retain more forest, gain more shrubs, gain less built (i.e., impervious) surface, retain less open water, and gain less total edge (fragmentation proxy) than PCD sites (Tilt and Cerveny 2013, Feinberg et al. 2015). We expected little to no change in landscape structure in either the forested Reserves or Developed sites as a corollary. Secondly, bird communities in C.D.s should be more stable than those in PCDs, and both should be less stable than forest reserves or existing Developed sites, as changing landscapes increase habitat heterogeneity, leading to increased species turnover (Connell and Slatyer 1977, Ewers and Didham 2006). Third, heterogeneity in avian assemblages should decrease more quickly through time in the CDs than PCDs, with both emerging subdivision forms increasing in heterogeneity relative to either forest reserves or previously Developed areas. Fourth, local (alpha) diversity should increase through time at both CDs and PCDs.

2.4 METHODS

2.4.1 *Study Area*

We studied landscape composition and avian communities in western Washington's Central Puget Lowlands (below 300m in elevation) across portions of eastern King and Snohomish Counties (Figure 1). The local maritime climate has moderate year-round temperatures and significant precipitation as rain, mainly during the non-summer months (Franklin and Dyrness 1973). The landscape is a mosaic of urban, suburban, and exurban development in the second-growth forest. In general, forest cover increases relative to development as one moves eastward from the city of Seattle toward the crest of the Cascade Mountain Range. Local forests are primarily a mixture of coniferous second growth featuring Douglas-fir (*Pseudotsuga menziesii*), western red cedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*) with substantial components of early successional hardwoods, e.g., red alder (*Alnus rubra)* (Franklin and Dyrness 1973).

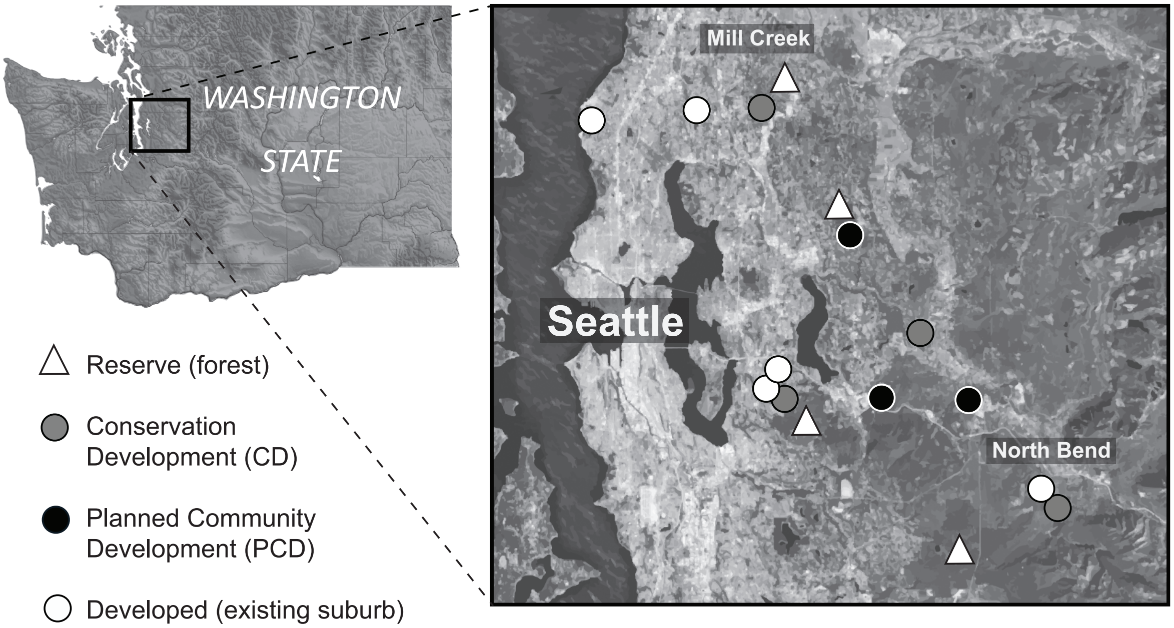

Figure 1. The study area (square) in Washington State (left) and enlarged (right) indicate locations of sixteen plots in three major landscape types: Reserve (4), Developed (5), and two types of subdivision forms: conservation developments (CD, 4) and planned community developments (PCD, 3), evaluated for landscape change and monitored for avian community composition from 1998-2010.

2.4.2 *Experimental Units*

Study sites were part of a long-term avian monitoring program initiated in 1998 (Donnelly and Marzluff 2004, Blewett and Marzluff 2005, Donnelly and Marzluff 2006). For this investigation, we sub-selected 16 study sites based on the duration of sampling across years in each of four land-use land-cover types/treatments: 1) four Reserve sites comprised of large tracts of relatively unfragmented secondary/tertiary growth forest, 2) five Developed sites comprised of existing suburban development, and two types of active subdivisions: 3) four low-intensity Conservation Developments (CD) sites and 4) three high-intensity Planned-Community Developments (PCD) (Figure 1). The design was quasi-experimental (Marzluff et al. 2015), consisting of replicated control and experimental sites, but lacking randomization of the treatment, i.e., conversion of landscape from forest to new suburbs (Manly 1992, Skalski and Robson 1992, Marzluff et al. 2015), and opportunistically identified future subdivisions.

2.4.3 *Prediction 1: Landscape Change*

2.4.3.1 Landscape Classification

To assess landscape characteristics over time, we collected and classified selected orthoimagery of all study sites between 1998 and 2010. To measure vegetative pattern and composition, we selected a 500-m radius buffer around each survey point at each study site (Figure 2). This distance represents both the approximate maximum linear expanse for all but the very largest avian breeding home ranges occurring in the study (e.g., American crow, *Corvus brachyrhynchos*; (Poole 2012) and previous studies relating bird communities to human-induced landscape modification (Tewksbury et al. 2002, Melles et al. 2003b). To quantify the change in structural heterogeneity of landscapes through time, we obtained all publicly available orthoimagery for the thirteen field seasons of avian monitoring. We augmented these records with aerial photography purchased from privately held archives. We used ArcGIS geographical information system software for classification (ESRI 2011). We measured five landcover categories in a two-part classification process. The first four cover types are modified from Blair (1996): forest, built (impervious surfaces such as buildings, roads, sidewalks), bare ground/grass (bare-ground, grass/lawn), and shrub (woody shrub or early seral/regenerating forest). We added a fifth cover type, open water (naturally occurring or engineered-retention ponds). We next used Object-Based Image Analysis (OBIA) (sensu Halabisky et al. 2011). OBIA is a multi-step process using SPRING software (Camara et al. 1996) where distinct objects are first identified based on spectral reflectance. Next, OBIA classifies imagery by iteratively identifying relevant multi-pixel objects using training data for each class. Because orthoimagery available during this period ranged from black and white (2 spectra), 3-spectra color, to 4-spectra color (3 visible spectra plus infrared), we further enhanced image interpretation through ocular inspection,

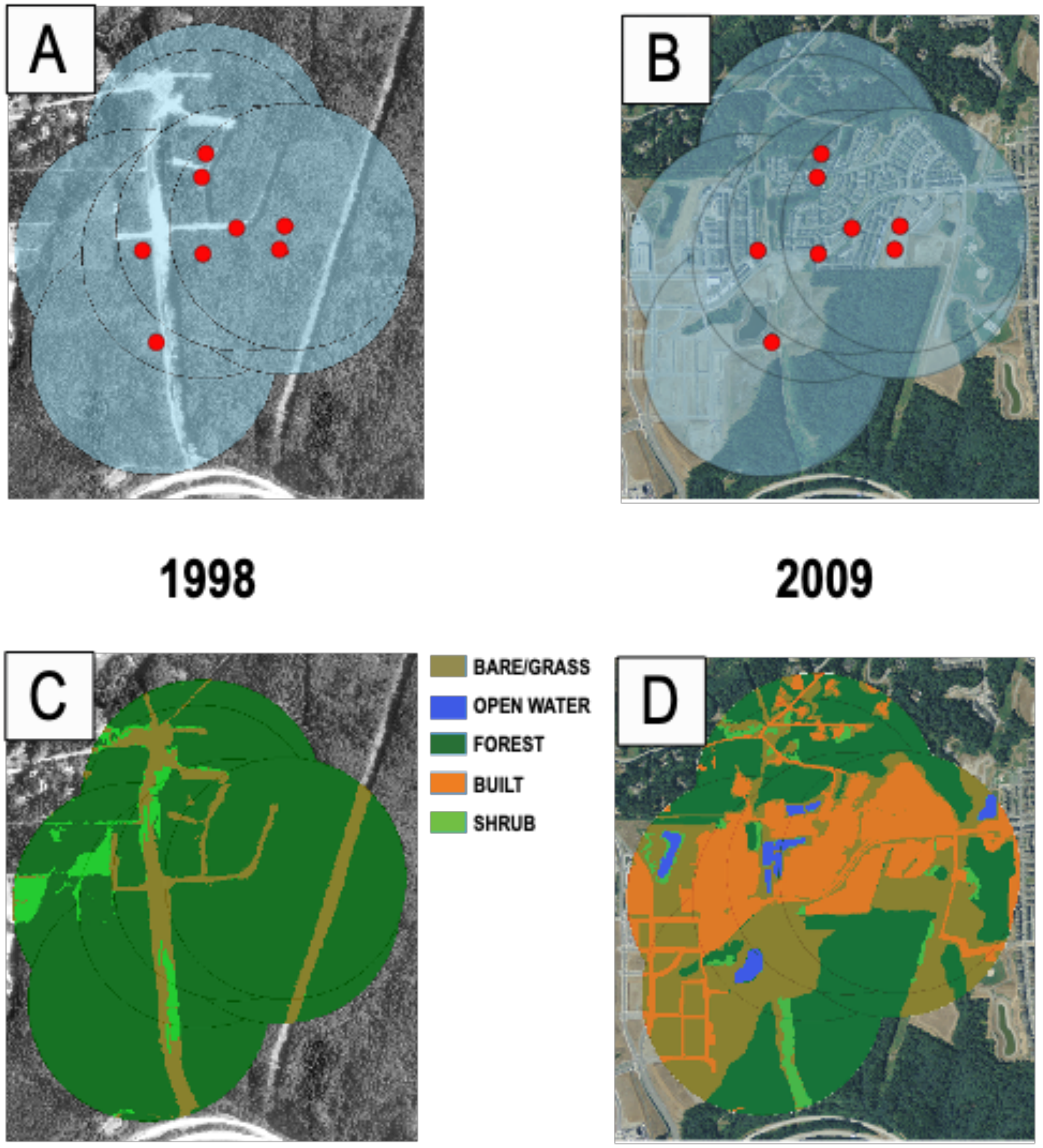

Figure 2. Spatial analysis using a temporal sequence of orthoimagery to produce classified maps in composition and configuration assessment of landscape change. The selected example is one of three Planned Community Developments (Issaquah Highlands; King County, WA) showing the initial landscape orthophoto in 1998 with superimposed 500-meter radial buffers (blue) around each of 8 avian point count (red circles) locations (A); the same site (B) at study conclusion in 2009; the classified maps illustrate five land cover categories (bare-ground / grass, open water, forest, built and shrub) for the same site in 1998 (C) and again in 2009 (D).

including a comparison of classified landscapes to historical imagery online (Google Earth, 2014), and edited classified landscapes by free-hand digitizing misclassified areas (Marzluff et al. 2015).

2.4.3.2 Classification Metrics

We calculated metrics for analyzing landscape composition and configuration using Fragstats software (Mcgarigal et al. 2002). We then quantified landscape composition using the class-level metric percent land cover (PLC). We selected total edge among all cover types (linear meters) to quantify spatial configuration, as both landscape fragmentation and overall land cover heterogeneity increase with a growing edge among classes. Because adjacent survey points were not spatially independent, we averaged all within-site metrics within classes across the 4-8 buffers at each study plot.

2.4.3.3 Statistical Analysis

We employed compositional analysis techniques (sensu Aitchison 1986) to test for differences in landscape cover classes between CD and PCD sites. Compositional data are proportional, subject to the unit-sum constraint, and require transformation to overcome the inherent lack of independence among categorical values. Because compositional analysis relies on log ratios, zeros are problematic (Fry et al. 2000). Therefore, we applied an additive log ratio (alr) transformation to values following Aitchison (1986). We used the combined product of the two proportionally minor cover classes (*shrub* and *open water*) as the denominator, with other classes used as the numerators in calculating log ratios.

We then modeled the alr-transformed landscape composition metrics for three habitat classes (forest, built, and grass/bare ground) and total edge across site types – Reserve, CD, PCD, and Developed sites – in the last year, landscape composition data were available using Bayesian linear models in JAGS (Plummer 2003, Plummer 2016, Kellner 2021) within R (R Core Team 2021). We fit four models, one with each of the landscape metrics as the response variable, where each model included categorical effects of site type. In addition, we assessed change in composition and configuration in CD and PCD sites only over the eleven annual intervals using Bayesian autoregressive broken stick models, also in JAGS. We built a series of models covering possible breakpoints, with separate breakpoints for CD and PCD sites, and we selected the model with the breakpoints for CD and PCD that resulted in the lowest Deviance Information Criterion value (DIC; Spiegelhalter et al. 2002) for inference.

2.4.4 *Predictions 2, 3 & 4: Bird Community Dynamics*

2.4.4.1 Bird Surveys

We surveyed bird communities in each study site during spring and summer (late March to early August) between 1998 and 2010, though not all sites were sampled in all years (Table 1). We monitored birds in several Reserve sites in 1998 and most actively transformed subdivision sites in 2000, after forest removal and initial housing and infrastructure construction.

Table 1. The number (n) of sites, by site type (Reserve = forest, Developed = existing subdivision, Conservation Development (CD = low-intensity development), Planned Community Development (PCD = high-intensity development) monitoring avian communities from 1998 to 2010 in the Central Puget Sound region of Washington State.

	Site Type			
Year	Reserve (*n* = 4)	Developed (*n* = 5)	Changing – CD (*n* = 4)	Changing – PCD (*n* = 3)
1998	2	0	0	0
1999	4	0	3	3
2000	0	5	4	3
2001	4	5	4	3
2002	3	3	4	3
2003	4	5	4	3
2004	4	0	4	3
2005	4	0	4	3
2006	4	0	4	3
2007	4	0	4	3
2008	4	1	4	3
2009	1	1	2	3
2010	3	5	4	3

We allocated eight randomly located avian survey points at each site with adjustments (one forested site had four survey points, while one changing site had five) for logistical considerations such as landowner permission (Donnelly and Marzluff 2004, Marzluff et al. 2015). All avian surveys were standard fixed-radius point counts, modified from methods outlined by Ralph et al. (1993); observers recorded all birds seen or heard within a 50-m radius circle during a 10-minute sampling period. We conducted all counts between sunrise and 12:30 pm PST. Observers trained for several weeks each season before data collection, emphasizing accurate visual and auditory identification, accurate distance measurement (i.e., < 50 m vs.> 50 m), and avoiding double-counting individuals already detected within each sampling interval. We visited each point count location four times per season; in rare instances, we could not complete the fourth visit due to changes in site access such as active forest clearing or construction.

We limited survey detections to those species with relatively small breeding territories or home ranges (Donnelly and Marzluff 2004, Marzluff et al. 2015). We excluded species considered transient, poorly sampled by our protocol, and those tied to non-representative habitats. Transient species were those seen or heard but not known to breed in our study area. Raptors and large-bodied woodpeckers possess large home ranges and thus were not well-sampled by our field protocol. Finally, we excluded species with natural histories tied to specific landscape or habitat elements, like water and dead and dying trees, thus eliminating most water or marsh birds and cavity nesters, respectively (Blewett and Marzluff 2005).

We conducted a complimentary distance-based sampling design in 2010 (Buckland 2001) to assess detection (Buckland et al. 1993, Mackenzie et al. 2002, Rosenstock et al. 2002, Thompson 2002). While fixed-distance sampling is appropriate for small bird surveys that rely on aural detection, especially in the heterogeneous, often linear landcover that is characteristic of suburban settings (Johnson 2008, Hutto 2016, 2017, Marques et al. 2017) our single season of distance sampling enabled us to gain some perspective on differential detection across landscape types (Marzluff et al. 2015). While we found no substantial differences in detectability across landscape types for individual species or the larger bird community, results suggested detectability (all species combined) was as much as 20% higher at points located in suburban land cover than in forested habitat.

2.4.4.2 Bird Community Statistical Analysis

We computed community-level metrics from bird survey data (species and abundances) to evaluate aspects of ecological succession: stability, heterogeneity, and diversity. For stability (prediction 2), or species turnover within sites, we calculated Chao-Jaccard abundance-based dissimilarity indices (Chao et al. 2005) for shared species composition in temporal intervals (successive pairs of years), using the dis.chao function in the CommEcol package (Adriano Sanches Melo 2021) in R (R Core Team 2021). When years were missing, we calculated the value between pairs of available years and then standardized the value by dividing by the number of years in the interval (e.g., if year three were missing, the stability metric would be calculated based on years 2 and 4 and then divided by 2). To calculate heterogeneity (prediction 3), or beta diversity, we applied this same estimator to all possible replicate pairs within site type in a given year. We estimated alpha diversity (prediction 4) using the ChaoShannon function in the iNEXT package (Hsieh et al. 2020) in R (R Core Team 2021). We selected these probabilistic estimators to address imperfect species detection (Nichols et al. 2000, Gotelli and Colwell 2001, Royle et al. 2005, Kissling and Garton 2006, Royle et al. 2007), such as "unseen" or rare species represented by few individuals, to reduce sampling biases common to many community-based indices (Chao et al. 2005). Although these estimated values have associated confidence intervals, we used values as point estimates (Chao et al. 2005).

We analyzed each community metric at two temporal scales. First, we considered the initial and final years of data collection, across all site types (Developed, Reserve, PCD, and CD). For seven of the sixteen sites (3 CD, 3 PCD, and 1 Reserve), the first and last years were 1999 and 2010, respectively. For six sites (5 Developed, 1 CD), the first and last years were 2000 and 2010, respectively. Among the remaining Reserves, 1998 and 2020 were the first and last years, respectively, for two, while 1999 and 2008 were first and last for one site. For stability, we modeled the Chao-Jaccard dissimilarity index calculated between the first and last year using a Bayesian model fit in JAGS (Plummer 2003) using the jagsUI package (Kellner 2021) within R

(R Core Team 2021). Because the index is bounded on 0-1, we assumed the data were beta-distributed and fit an effect of site type. We included all within-site type pairs for the first and last year for heterogeneity. We again assumed a beta error structure and fit a nested effect of site type within a year. For diversity, we modeled the index in the first and last years for each site, again with a nested effect of site type by year. For diversity, we assumed data were normally distributed.

Next, we considered a finer resolution of annual change between 1998 and 2010 for the PCD and CD sites. Most available intervals between bird surveys were one year; however, a few intervals were two years between surveys. We modeled the interval estimates for CD and PCD sites using autoregressive broken stick models fit in JAGS (Plummer 2003, Plummer 2016) using the jagsUI package (Kellner 2021) within R (R Core Team 2021). We again assumed the response was beta-distributed for stability and heterogeneity and that diversity was normally distributed. We built models with all possible break points in our time series (with separate breakpoints for PCD and CD sites), and we selected the model with the lowest DIC value (CITE) for inference.

2.5 RESULTS

2.5.1 *Prediction 1: Cover class composition and configuration across landscape types*

Developing sites changed quickly through time. Raw landcover proportions plotted for CD and PCD sites show significant structural conversion by residential development during the study period, with loss of forest and an increase in built area, grass/bare ground, and total edge (Figure 3).

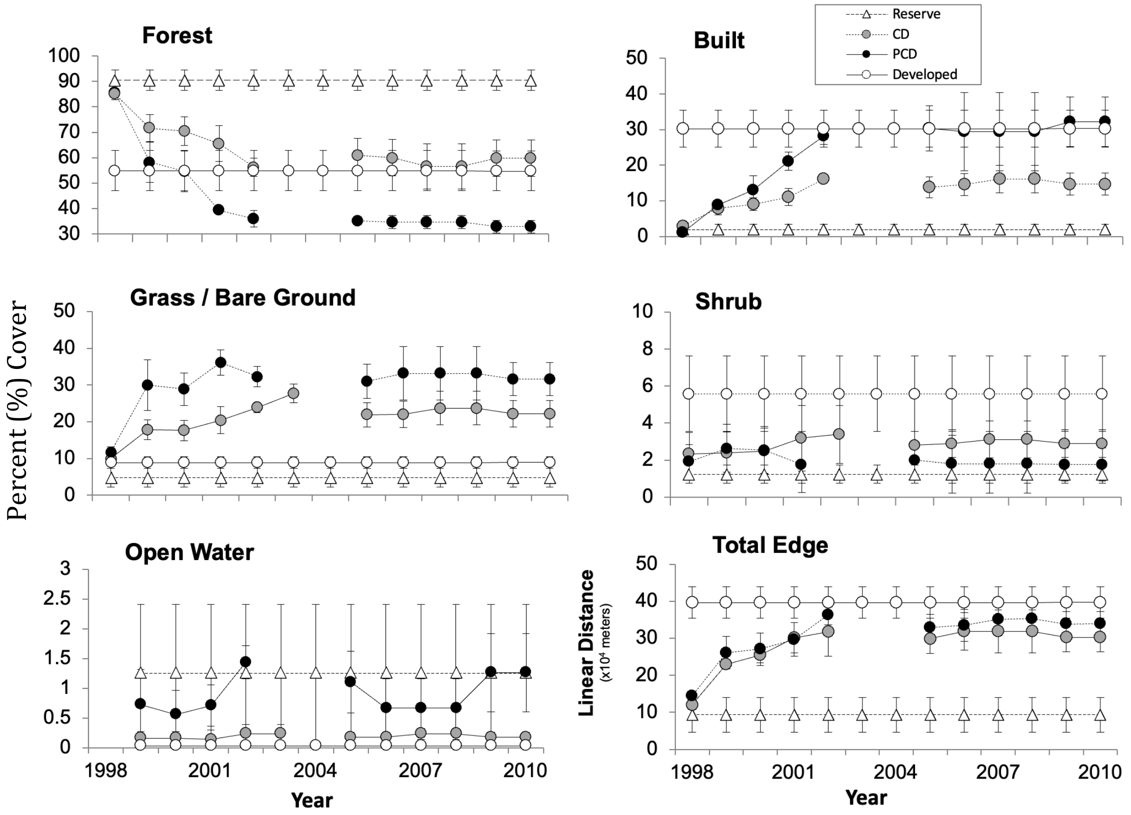

Figure 3. Landcover composition and configuration (untransformed) values for percent cover classes of forested, built (impervious surface), bare ground/grass, shrub, open water, and total edge (meters) at Reserve (forest), Conservation Development (CD), Planned Community Development (PCD) and Developed (existing suburb) sites based on orthoimagery classification from 1998-2010 in Central Puget Sound region of Washington State. Orthoimagery was not available for all sites in all years; after analyzing a subsample of Reserve and Developed sites, we confirmed no significant landcover change occurred in these site types during the study period and classified a single year of orthoimagery for each. Scales are adjusted among panels to view temporal trends more easily.

PCD sites lost forest and added built area faster than CD sites, even though both had similar final outcomes. Orthoimagery did not exist for all sites in all years of the study (1998-2010). The absence of chronological imagery was particularly pronounced among Reserve and Developed site types; thus, we classified a subset of sites using the first (2000) and last (2009) years available and determined that no substantial change in landscape characteristics had occurred during this period (Figure 3). The statistical analysis for the last year of landscape composition and total edge across all sites generally confirmed the landscape change predictions. Landcover in CDs was less intensively altered than in PCD sites. Both these subdivision forms were similar, although less developed than nearby suburbs; however, credible intervals were large and could not provide robust differentiation among cover classes across sites (Figure 4). We calculated all pairs of differences between site types for each landscape metric and the 95% credible intervals on the differences excluded 0 only for forest cover between Reserves and PCD sites (Reserve > PCD), and all comparisons for total edge (Developed > CD > PCD > Reserve.

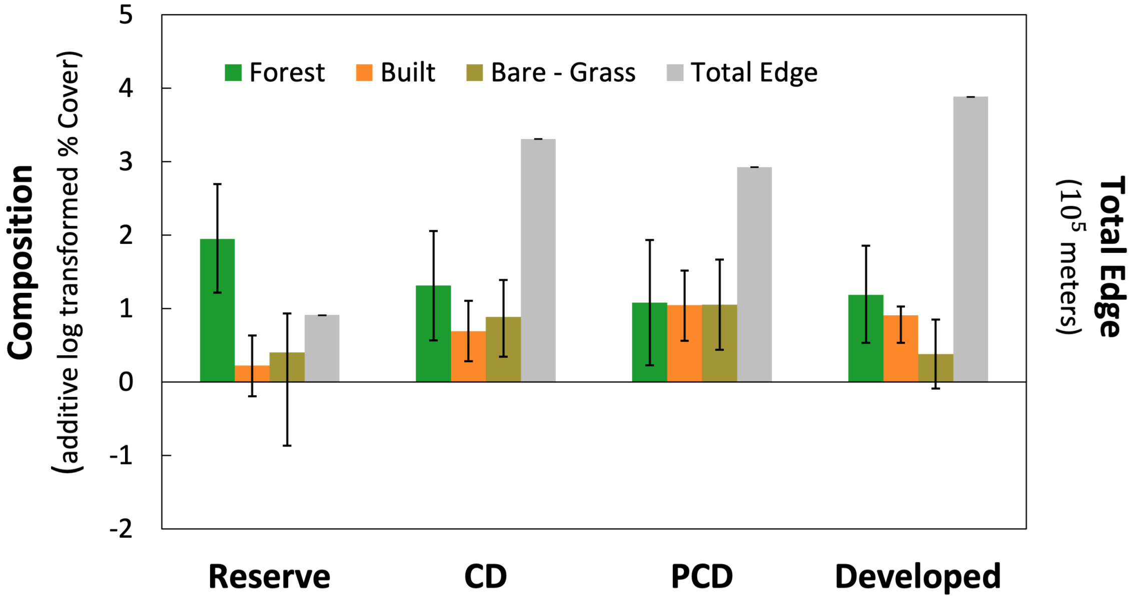

Figure 4. Landcover Change Analysis: mean % cover type (additive linear ratio transformed values) for the composition of the forest, built (impervious surface), bare ground/grass, shrub, open water, and total edge (10^5meters), and Bayesian 95% credible interval bounds (lower, upper) for 16 classified site maps (from orthophotographs) from1998-2010 in Central Puget Sound region of Washington State.

The pace of change in composition and configuration of landcover within changing sites differed depending on the form of development. PCD sites lost forest and added built area more quickly than CD sites, even though both had similar values by the end of the study (Figure 5).

Total edge, representing landscape fragmentation, also increased more rapidly at PCD than CD sites.

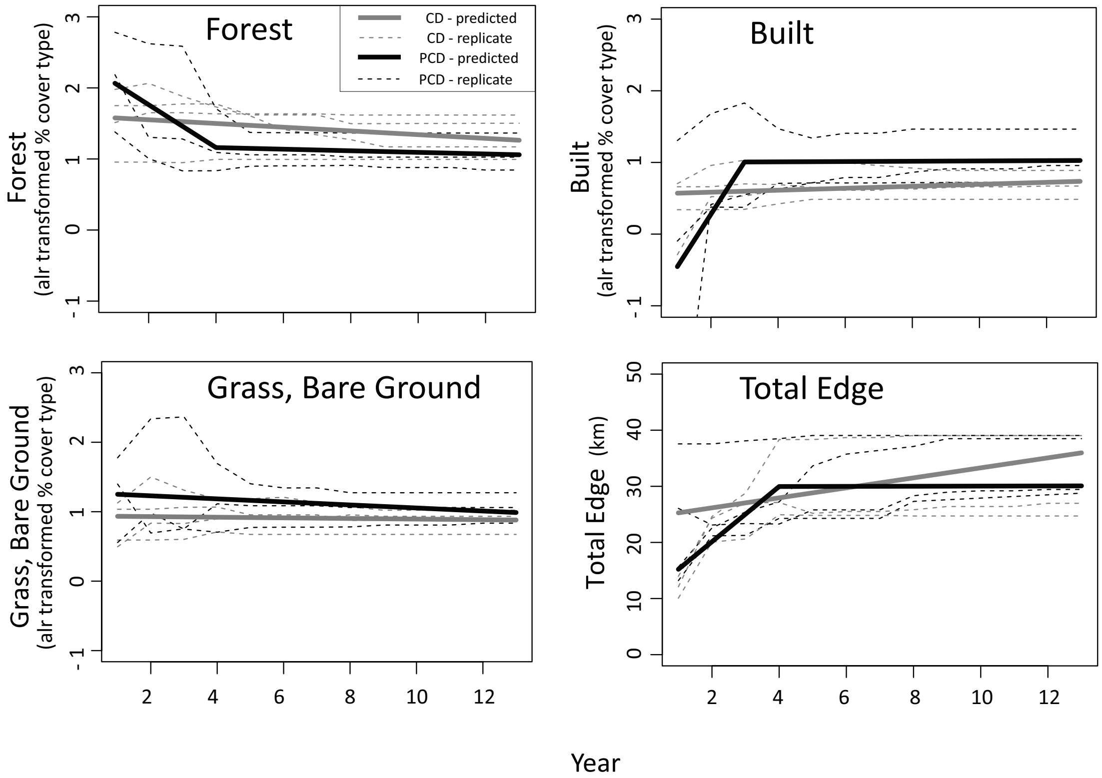

Figure 5. Broken stick regression models for variable intensity development subdivisions, Conservation Developments (CD) and Planned Community Developments (PCD), derived from available orthophotography for 1998-2010 in the Central Puget Sound region of Washington State. Trend lines represent the best fit (Bayesian framework) overall and replicate models for development type cover classes (additive linear ratio transformed percent cover) for the area forested, built (impervious surface), bare ground/grass, shrub, open water, and total edge (meters) measures landscape structure /configuration.

2.5.2 *Bird Community Dynamics*

2.5.2.1 Stability of Bird Communities

Bird community stability differed among landscape types as expected over the coarse time scale (earliest available to latest available years). The highest stability (lowest dissimilarity index value) occurred among the Reserves, followed by the Developed, CD, and PCD sites (Figure 6).

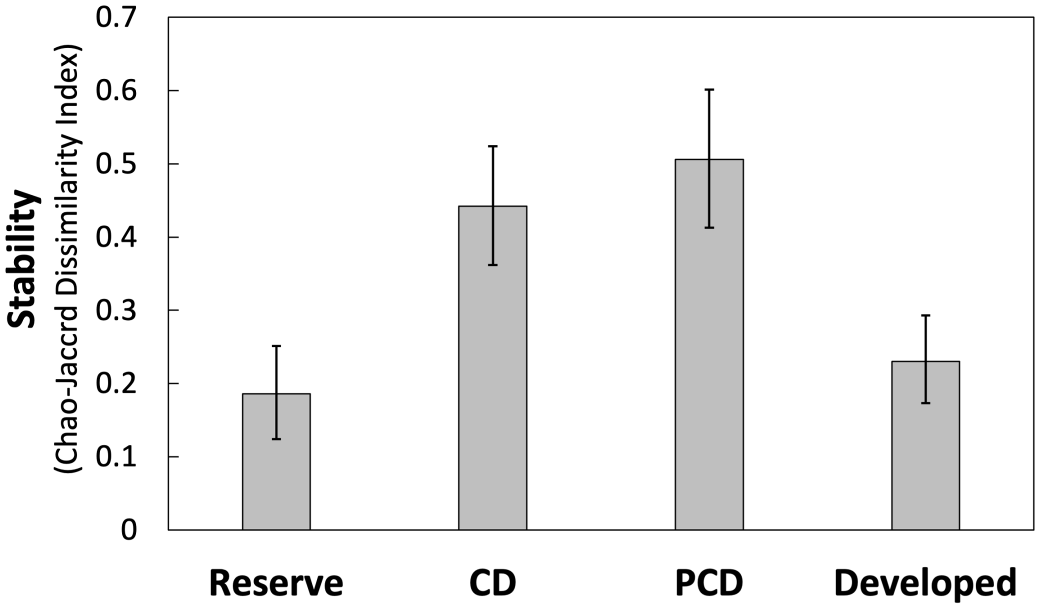

Figure 6. Stability: Mean Chao-Jaccard dissimilarity index (non-parametric, abundance-based; species composition comparison within replicate paired by year) and Bayesian 95% credible interval bounds (lower, upper) calculated for change (first and last years) in avian assemblages at 16 sites monitored from 1998 to 2010 in the Central Puget Sound region of Washington State.

Bird communities in PCDs stabilized slower than C.D.s when modeled at a finer temporal scale (Figure 7). Bird communities in both subdivision forms experienced instability from the start of the study, with sharp corrections (decreasing dissimilarity) over several time intervals. In the broken stick analysis, the existence of inflection points was strongly supported over a null model, with no breakpoints ($\triangle$ DIC = 19.9). Both development types experienced slight destabilization following their inflection points, ultimately arriving at comparable levels by the end of the monitoring period.

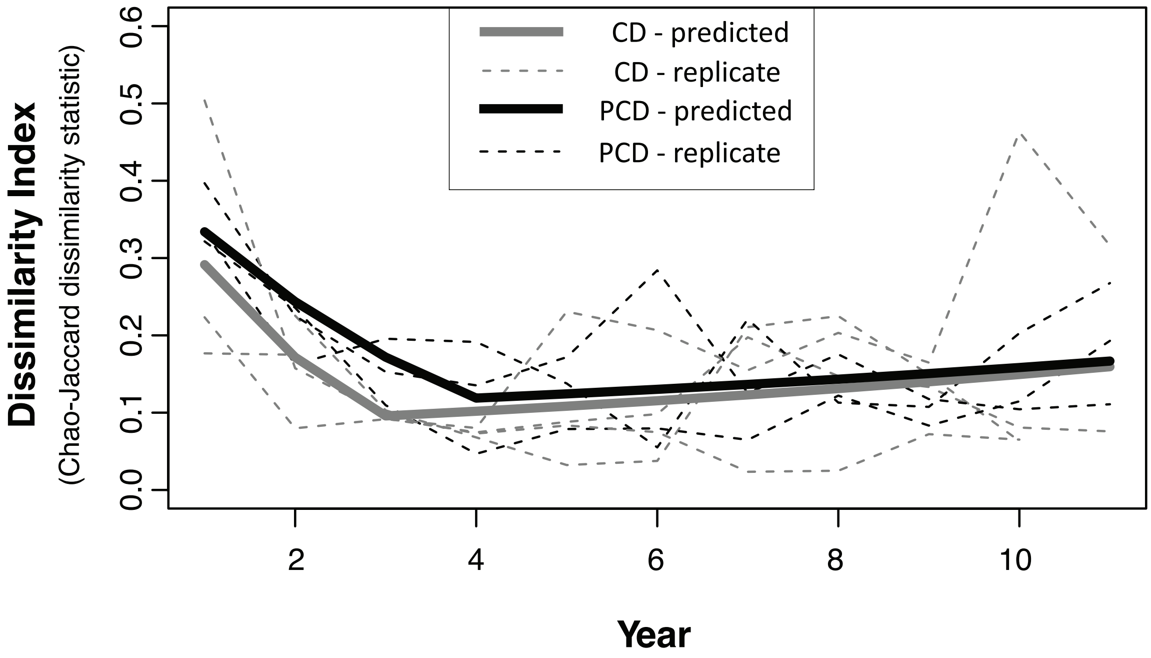

Figure 7. Stability of bird communities in variable density subdivisions; broken stick beta regression models for community dissimilarity index (Chao-Jaccard dissimilarity statistic), calculated as interannual within sites comparisons, analysis for subdivision Conservation Developments (CD) and Planned Community Developments (PCD);1998-2010 in Central Puget Sound region of Washington State.

2.5.2.2 Heterogeneity of Bird Communities

Heterogeneity, or dissimilarity of bird species assemblages within landscape types, was equivocal at the coarse scale (first and last available years) but more revealing in the annual comparisons among subdivision forms. When considering start and ending years across all landscape types, avian community heterogeneity of Reserves, Developed , and CD sites were relatively unchanged (Figure 8). However, in contrast to the other sites, birds in PCD sites demonstrated a net increase in heterogeneity.

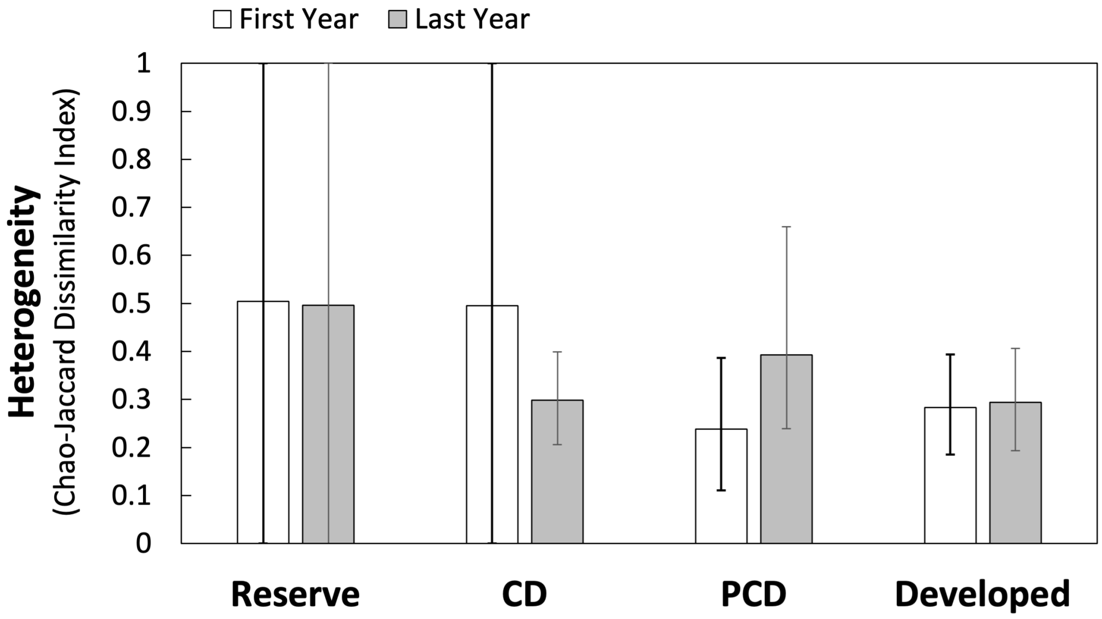

Figure 8. Heterogeneity: Mean Chao-Jaccard dissimilarity index (species composition comparisons for all possible replicate pairs in given years; non-parametric, abundance-based) and Bayesian 95% credible interval bounds (lower, upper) calculated for change (first and last years) in avian assemblages at 16 sites monitored from 1998 to 2010 in the Central Puget Sound region of Washington State.

Modeled at annual intervals, bird communities decreased in heterogeneity among both active development types, then increased again. The rate of change was lower at PCD sites relative to CD sites (Figure 9). Heterogeneity inflection points were later than those recorded for stability (by one-year interval), with CD sites hitting a breakpoint in year four and PCD sites in year five. The best fit model was strongly supported over the null model, with no breakpoints (△DIC = 19.9).

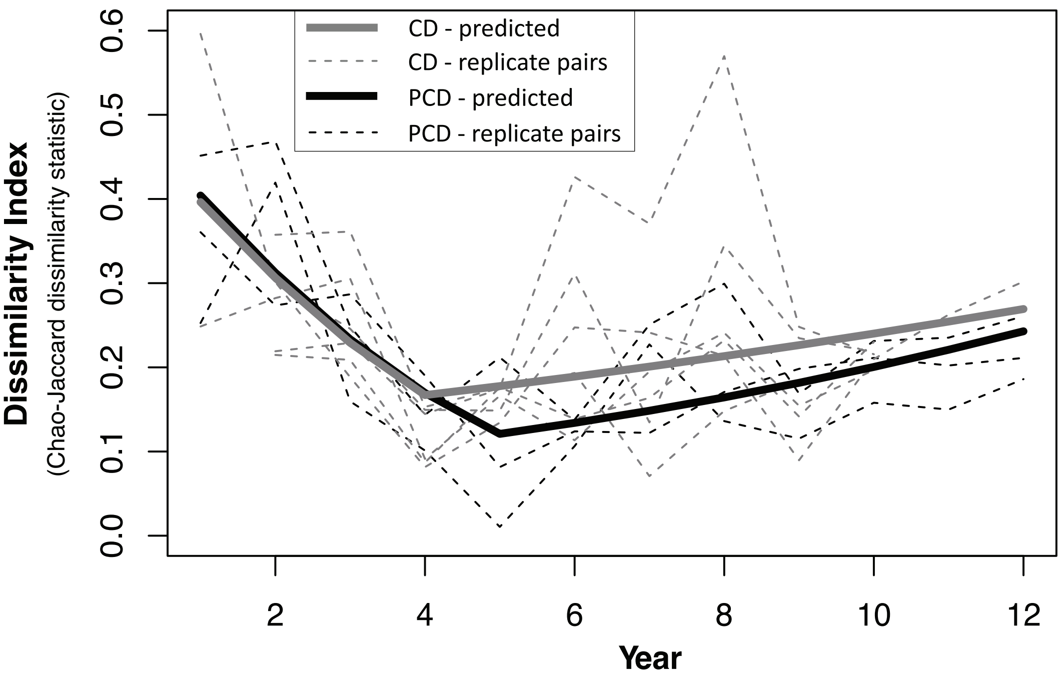

Figure 9. Heterogeneity of bird communities in variable density subdivisions; broken stick beta regression models for community dissimilarity index (Chao-Jaccard dissimilarity statistic), calculated for all possible pairs of replicates for each given year) analysis for subdivision Conservation Developments (CD) and Planned Community Developments (PCD);1998-2010 in the Central Puget Sound region of Washington State.

2.5.2.3 Diversity of Bird Communities

At the coarse time scale, avian diversity behaved mainly as we predicted (Figure 10). Mean diversity was flat through time at the Reserve sites. Mean bird diversity increased in the CD and PCD sites, though not significantly (based on overlapping 95% CI). Surprisingly, however, existing developments posted significant increases in diversity (based on non-overlapping 95% C.I.s for the Developed effects in the first and last year), despite little change in land cover during the study.

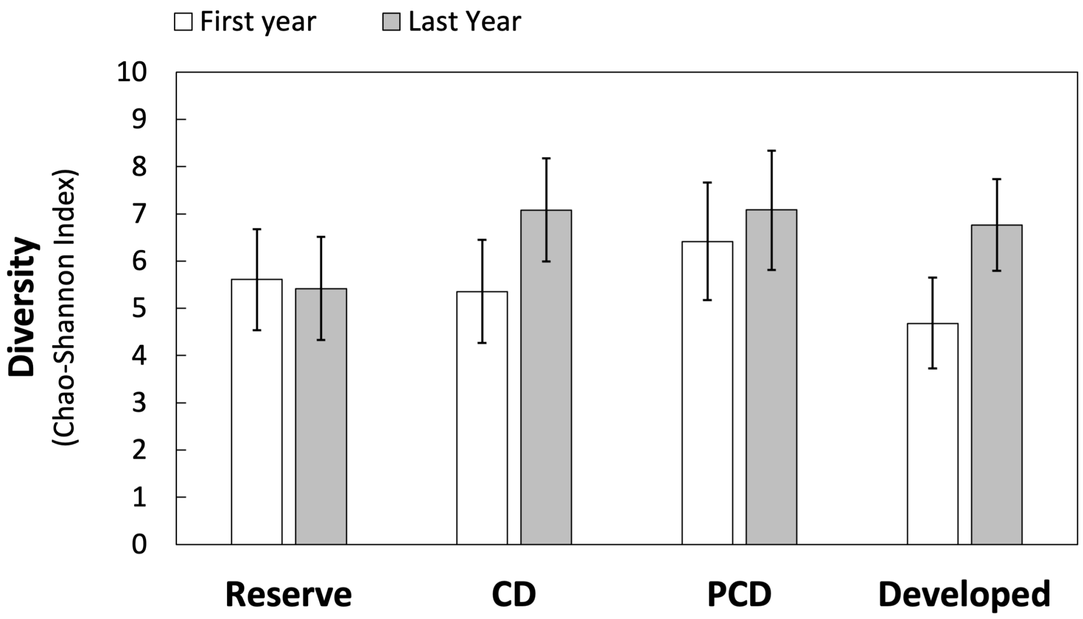

Figure 10. Diversity: Mean bird diversity (Chao-Shannon index; non-parametric, abundance-based) and Bayesian 95% credible interval bounds (lower, upper) calculated (first and last years) at 16 sites monitored from 1998 to 2010 in the Central Puget Sound region of Washington State.

Finer grain modeling of CD and PCD sites showed both new subdivision forms proceeding at similar rates (Figure 11). Both subdivision forms showed an initial decrease in avian diversity over the first decade of the study, followed by a sharp increase near the end.

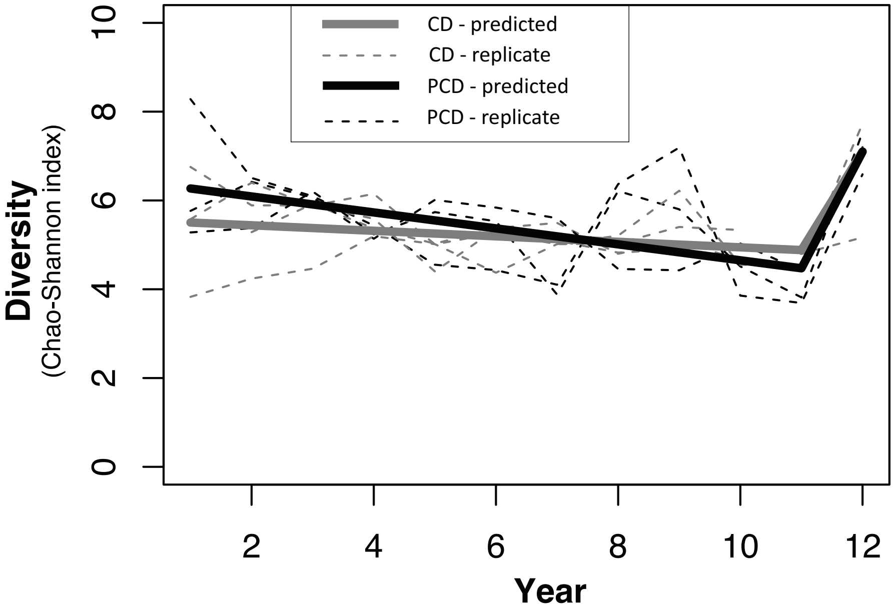

Figure 11. Diversity of bird communities in variable density subdivisions; broken stick regression models for bird community dissimilarity index (Chao-Jaccard dissimilarity statistic), calculated for all possible pairs of replicates for each given year) analysis for subdivision Conservation Developments (CD) and Planned Community Developments (PCD);1998-2010 in the Central Puget Sound region of Washington State.

2.6 DISCUSSION

2.6.1 *Community Succession & Anthropogenic Disturbance*

Empirical tests of predictions from succession theory are rare (Miller and Terhorst 2012), even more so within anthropogenically disturbed systems (Paine et al. 1998). Urbanization, or alteration of land use, is broadly considered a form of anthropogenic disturbance (Peters et al. 2011, Newman 2019) capable of changing bird communities through time (Slabbekoorn 2013, Aronson et al. 2014, Beninde et al. 2015, Marzluff 2017, Seress et al. 2020). Debate in theoretical framing exists, however, with some asserting urbanization so transforms affected areas that the process ceases to be an actual ecological "disturbance" and instead requires an entirely new model to accommodate chaotic system dynamics. Such systems are known as

Social-Environmental-Technological systems (SETs; (Grimm et al. 2017). Alternatively, urbanization may have relationships with other types of ecological disturbances that result in post-disturbance successional processes. We tested this hypothesis by evaluating bird community stability, heterogeneity, and diversity in a rapidly urbanizing setting (Decker et al. 2017). Our findings, relative to past urban gradient studies of avian community succession (Alberti 2005, Chace and Walsh 2006, Marzluff et al. 2008, Pickett et al. 2011, Riem et al. 2012, Beninde et al. 2015, Bai et al. 2017), provide a temporally finer grain understanding of how succession can structure animal communities.

Initial disturbance intensity (land cover change) produced high community instability and low heterogeneity among bird assemblages (Mckinney 2006, Devictor et al. 2007). Bird communities stabilized as the construction phase came to completion, attaining the minima for species turnover (instability) in three to five years. However, our study suggests a possible threshold in stability as local species turnover once again intensified. Community assemblage differences (heterogeneity) also increased after a period of steady decline, although not to previous levels. The quadratic shape of both stability and heterogeneity were outcomes not predicted by conventional ecological succession (Miller and Terhorst 2012).

Avian community diversity in both subdivision types was somewhat depressed for much of the study, with sharp net gains in avian species near the study end, a novel finding based on the literature. Urbanization, at least for birds, is a "press" (constant ecologically modifying force) rather than a 'pulse' (temporally finite perturbance) form of disturbance (Underwood 1994, Arens and West 2008, Lowry et al. 2013). Clearing native vegetation for development presents a locally novel habitat for early successional species (Mckinney 2006), but at the expense of some native forest specialists (Hansen et al. 2005a, Hansen et al. 2005b, Lussier et al. 2006, Marzluff et al. 2015). As humans take up residence in new settlements, the nature of disturbance shifts qualitatively. Anthropogenic inputs such as vehicular traffic, companion animals, bird feeders, edible gardens, and outdoor recreation (Hostetler et al. 2005, Hostetler and Drake 2009, Hostetler and Noiseux 2010, Loss et al. 2015) directly impact bird survival and reproduction by further degrading habitat quality for some species while enhancing it for others (Chace and Walsh 2006). Construction of new residences and associated infrastructure offers synanthropic species new nesting habitat (Morelli et al. 2014, Wang et al. 2015, Tomasevic and Marzluff 2017).

Despite over a decade of investigating our study system, outcomes for the structure of local bird communities in the suburbs remain indeterminate. The successional predictions we tested suggest that avian assemblages in two common regional forms of subdivision development are more stable, less heterogeneous, and more diverse than before development activity; however, changes at these sites continue (Rebele 1994). Consequently, we propose an emergent form of community succession occurring in landscapes heavily, but not wholly, modified by modern humans. Tertiary succession (Figure 8) could apply to the restructuring of communities (e.g., birds or other wildlife) impacted by anthropogenic disturbance coupled with long-term human maintenance of at least some system components and or ecological processes, such as widespread suburban development occurring in exurban landscapes. We propose a modified form of secondary succession in developing suburbs, tertiary succession, that allows for variable outcomes in functional communities through time (Figure 12).

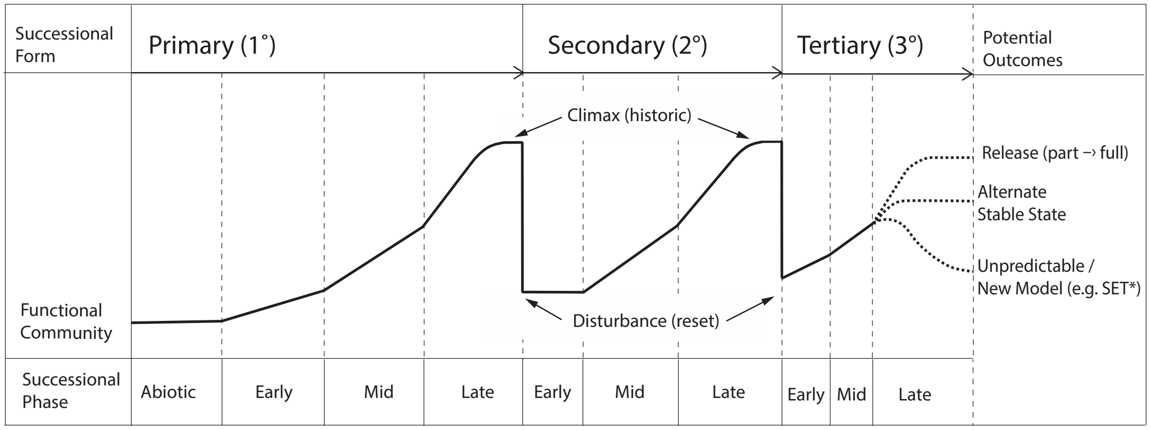

Figure 12. A conceptual model for existing (primary, secondary) and proposed (tertiary) forms of community succession. Primary succession initiates after a natural disturbance, while secondary succession may proceed following a "natural" or "anthropogenic" disturbance. Tertiary succession results from exclusively anthropogenic disturbances that are ALSO human maintained (in part or whole) indefinitely, with variable outcomes. *Social-Ecological-Technological system (see Grimm et al. 2017).

Following initial landscape modification (deforestation, residential construction), bird communities may experience a) release (partial to complete), b) alternate stable state(s), to c) system reorganizations so extreme as to requiring of new integrative models.

Urbanizing lands can undergo forms of release from past disturbances and achieve conditions more similar to historic climax communities such as the recent reforestation occurring in parts of the southeastern (Twedt 2004) and northeastern U.S. (Foster et al. 1998, Foster et al. 2002). The stability, heterogeneity, and diversity in suburban bird communities may reach plateaus, leading to alternate stable states in the future (Beisner et al. 2003). However, if anthropogenic disturbances continue to press avian habitat conditions in novel ways, such as infill development (Newton et al. 2017), more complex integrated models (Grimm et al. 2008, Grimm et al. 2017) may be necessary to accurately describe the change in bird community assemblages (Mckinney 2006, Devictor et al. 2007, Blair and Johnson 2008, Pickett et al. 2011, Lin and Fuller 2013).

2.6.2 *Conserving Birds in Modified Lands*

Research has generated numerous insights into the successful management of birds in urbanizing lands (Savard et al. 2000, Marzluff et al. 2001, Marzluff and Ewing 2001, Chace and Walsh 2006, Shustack and Rodewald 2008, Magle et al. 2012, Lowry et al. 2013, Aronson et al. 2014, Marzluff 2017, Campbell et al. 2022). Less known are the potential trade-offs for managing birds inhabiting differing suburban development forms (Hostetler et al. 2005). Our study contributes to a greater understanding of how the landscape transformation process may predict future conditions and commensurate avian species assemblages (Hansen et al. 2005a).

Lower density conservation developments often retain more native forest (Robinson and Brown 2009) and add less built landcover (structure, paved) than planned communities. Built land cover was more spatially diffuse among subdivisions in our study than is typically noted for conservation developments (Lenth et al. 2006, Farr et al. 2017). Consequently, habitat fragmentation, measured by total edge, was similar to the higher intensity development categories found here and elsewhere (Irwin and Bockstael 2007).

Considerable debate exists as to whether diffuse versus clustered development is most advantageous for maintaining avian biodiversity (Blair and Johnson 2008, Lin and Fuller 2013, Geschke et al. 2018). Our finding that changes in bird community stability and heterogeneity delayed in PCDs relative to CDs suggests the benefit of limiting the frequency and extent of more intensive subdivision development at the landscape scale. Analogous concerns exist for conserving birds in another human-dominated system, agricultural lands. Here, studies suggest that low-intensity compromise "land sharing" favors common, widespread species, while "land sparing" benefits native specialist species (Baudron and Giller 2014, Fischer et al. 2014, Stott et al. 2015). The extent and frequency of habitat modification are likely more significant in the agricultural context; however, the primarily organic (non-synthetic) nature of landscape features there should increase bird community plasticity in the future than the relatively high imperviousness of suburban land use.

Multiple findings from our study area have confirmed that regional exurban/suburban developments, including those in existence for multiple decades, continue to maintain high avian diversity relative to nearby urban areas (Donnelly and Marzluff 2004, Blewett and Marzluff 2005, Hepinstall et al. 2008, Whittaker and Marzluff 2009, Marzluff et al. 2015, Marzluff et al. 2016, Marzluff 2017). Thus, C.D.s and PCDs, which will necessarily be less built than strictly urban areas, are unlikely to suffer overall species loss through biotic homogenization (Crooks et al. 2004, Alberti 2005, Devictor et al. 2007, Croci et al. 2008, Van Rensburg et al. 2009). However, forest specialists are likely to be replaced by characteristic, native early successional species (Blair 1996).

2.6.3 *Limitations and future directions*

Temporal gaps in data availability for landscape and avian assemblage change constrain some analyses, namely annual change in Reserve and Developments. In addition, detectability is a concern when sampling animal communities, especially birds (Smith et al. 1998, Nichols et al. 2000, Riffell and Riffell 2002, Rosenstock et al. 2002, Dorazio et al. 2006, Kissling and Garton 2006, Royle et al. 2007, Simons et al. 2007, Newson et al. 2008, Brewster and Simons 2009, Rota et al. 2009). We did not incorporate potential actors operating at the regional scale, such as biogeographical constraints on species (Cornell and Lawton 1992, Whittaker et al. 2001) or the impacts of landscape change outside the boundaries of study sites, which may play a role in the inter-annual change in local species composition (Cam et al. 2000, Graves and Rahbek 2005). Future analysis will focus on the response of select species to habitat differences in the two sub-development types. Do forest specialist birds decline slower (e.g., local extinction rates) in the more forested Conservation developments? Perhaps early successional or synanthropic species increase faster (e.g., colonization rates) amidst the greater built area and more extensive bare ground/grass of the Planned Community Developments? Where do forest specialists go when humans alter their habitat? Future research studies could seek evidence for displaced birds crowding into remaining forest patches by evaluating species abundances separately in forested and suburban habitats within each site. Lastly, this longitudinal study did not collect data on birds outside the breeding seasons, though future assessment of winter use would greatly inform the relative value of sites for resident bird species during a critical period in their annual survival (Smith 2003, Atchison and Rodewald 2006).

2.7 LITERATURE CITED

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Chapter 3. A TALE OF TWO SUBURBS: INFLUENCE OF NEW RESIDENTIAL CONSTRUCTION ON BIRD ABUNDANCES

3.1 ABSTRACT

Human population growth and changing settlement patterns fuel increased residential development of urban fringe lands. The establishment of variable density suburbs is increasingly the focus of avian conservation concerns. We conducted a long-term (12 years) study of bird abundance, examining human-tolerance guilds and individual species in relation to deforestation and subdivision construction in metropolitan Seattle, Washington. Lower intensity conservation developments (CD) tended to maintain more native forest birds (avoiders of human development) and exclude synanthropic (exploiters of human development) species relative to higher intensity planned community developments (PCD). Total avian abundance and avian generalist (adaptors to human development) species were similar across CD and PCD sites. Bird abundance within guilds was dominated by a small number of member species, suggesting a more complex interplay of traits determines avian population dynamics among these anthropogenically altered lands. We did not detect local species extinctions or significant biotic homogenization of bird communities in either subdivision form during the study.

3.2 KEYWORDS

Landcover change, urban birds, subdivision, suburban development, abundance, guild, synanthropic, Adaptor, Avoider, Exploiter, Seattle, Washington state

3.3 INTRODUCTION

Human population growth and changing settlement patterns fuel global urbanization, leading metropolitan areas to swell through densification and expansion (Seto et al. 2011, Buhaug and Urdal 2013, Esch et al. 2017). The resulting modification in land use subsequently restructures plant and animal communities (Paine et al. 1998, Marzluff et al. 2001, Lepczyk et al. 2008, Marzluff et al. 2008, Pickett et al. 2011, Lowry et al. 2013, Beninde et al. 2015, Pejchar et al. 2015).

Exurban and rural lands at the fringe of metropolitan boundaries may experience dramatic landscape modification as native habitats and agricultural areas are subdivided into residential housing and associated infrastructure (Theobald 2001, Hansen et al. 2005a, Robinson et al. 2005, Ikin et al. 2014, Geschke et al. 2018). The inevitability of continued suburbanization surrounding many cities necessitates a greater understanding of this landscape modification's impacts on local and regional ecological processes (McDonald et al. 2020). Paramount in these efforts is the assessment of the effects of residential development on birds and bird habitats (Marzluff et al. 2001, Fraterrigo and Wiens 2005, Chace and Walsh 2006, Chapman and Reich 2007, Blair and Johnson 2008, Merenlender et al. 2009, Huste and Boulinier 2011, Lin and Fuller 2013, Ikin et al. 2014, Geschke et al. 2018).

Aggregating species responses by functional guilds has proved valuable in many community ecology contexts (Blaum et al. 2011). Birds inhabiting urbanizing landscapes are regularly grouped by their tolerance of human development (Blair 1996): Avoiders (native habitat specialists), Adapters (early successional species), or Exploiters (synanthropic habitat generalists). In this study, we evaluate several approaches to quantifying bird community dynamics, which can help produce information to aid land managers and urban planners in conserving avifauna in variable density suburbs, namely, human-tolerance guild responses species-specific responses in both conservation and master-planned community residential development. Conservation developments studied elsewhere are generally lower in housing density, with residential structures more clustered together and retaining more native vegetation than master-planned communities (Hostetler and Noiseux 2010, Tilt and Cerveny 2013, Feinberg et al. 2015). Conservation developments in our study were more diffuse than clustered in configuration relative to other systems (DeLap 2022).

Building on past research on birds (Donnelly and Marzluff 2004, Blewett and Marzluff 2005, Hepinstall et al. 2008, Marzluff et al. 2008, Whittaker and Marzluff 2009), landscape change (Marzluff et al. 2015, DeLap 2022) and human-tolerance guild associations (Donnelly and Marzluff 2004, Shryock et al. 2017) we developed several predictions. Because conservation development sites retained more natural habitat, though they were as fragmented as planned communities, we predicted they would hold a higher abundance of birds than the master-planned developments (prediction 1). We also expected the relative abundance of Avoiders and Adapters to be highest in the conservation developments (predictions 2a and 2b). At the same time, birds in the Exploiter guild would dominate in the more intensely developed master-planned communities (prediction 2c). Finally, we expected differences in overall guild performance relative to member taxa. We based guild definitions on the degree to which species that were *a priori* grouped (Shryock et al. 2017) into the same guild had similar responses to each other and the guild overall; we expected dominant trends for each guild would reflect >50% of the species members for that guild (predictions 3a-3d). We collected data on bird communities in urbanizing landscapes of western Washington State and analyzed them to evaluate the above predictions.

3.4 METHODS

We conducted our study over 13 years (1998-2010) at sites actively converting from forest (largely mixed coniferous-hardwood second growth, Franklin and Dyrness 1973) to variable-density residential housing within the lowlands of Central Puget Sound, Washington State (Figure 1) (Marzluff et al. 2015, DeLap 2022). We classified subdivisions into two configurations based on our earlier landscape analysis (DeLap 2022) with three high-density Planned Community Developments and four Conservation Developments, hereafter referred to as PCD sites and CD sites, respectively (Figure 1). Ultimately (2010), PCD sites were generally lower in forest cover and higher in built cover, including residences and other impervious surface infrastructure, while CD sites were more diffuse in the arrangement of anthropogenic structures but equivalent in the overall degree of landscape fragmentation (DeLap 2022).

We surveyed avian communities using fixed radius point counts (Ralph et al. 1993), with multiple visits over each breeding season (Donnelly and Marzluff 2004, Marzluff et al. 2016). For analyses, we considered 58 response variables: overall indices of abundance, indices of abundance for three human-tolerance guilds (Avoiders, Adapters, Exploiters), and abundance indices for 54 individual species. We grouped species into human-tolerance guilds based on natural history traits and past research on bird abundances along urbanization gradients (Blair 1996). We modeled counts for each year averaged over visits and point count locations within each site (Blair 1996, Shryock et al. 2017) using general linear mixed models with random effects of site and fixed effects of development type (CD, PCD), year (time) quadratic function of time ($time^2$) and interactions for site x time, site x $time^2$. We conducted all statistics in SPSS (IBM Released 2015) and applied a model selection framework to rank candidate model performance (Burnham and Anderson 2010).

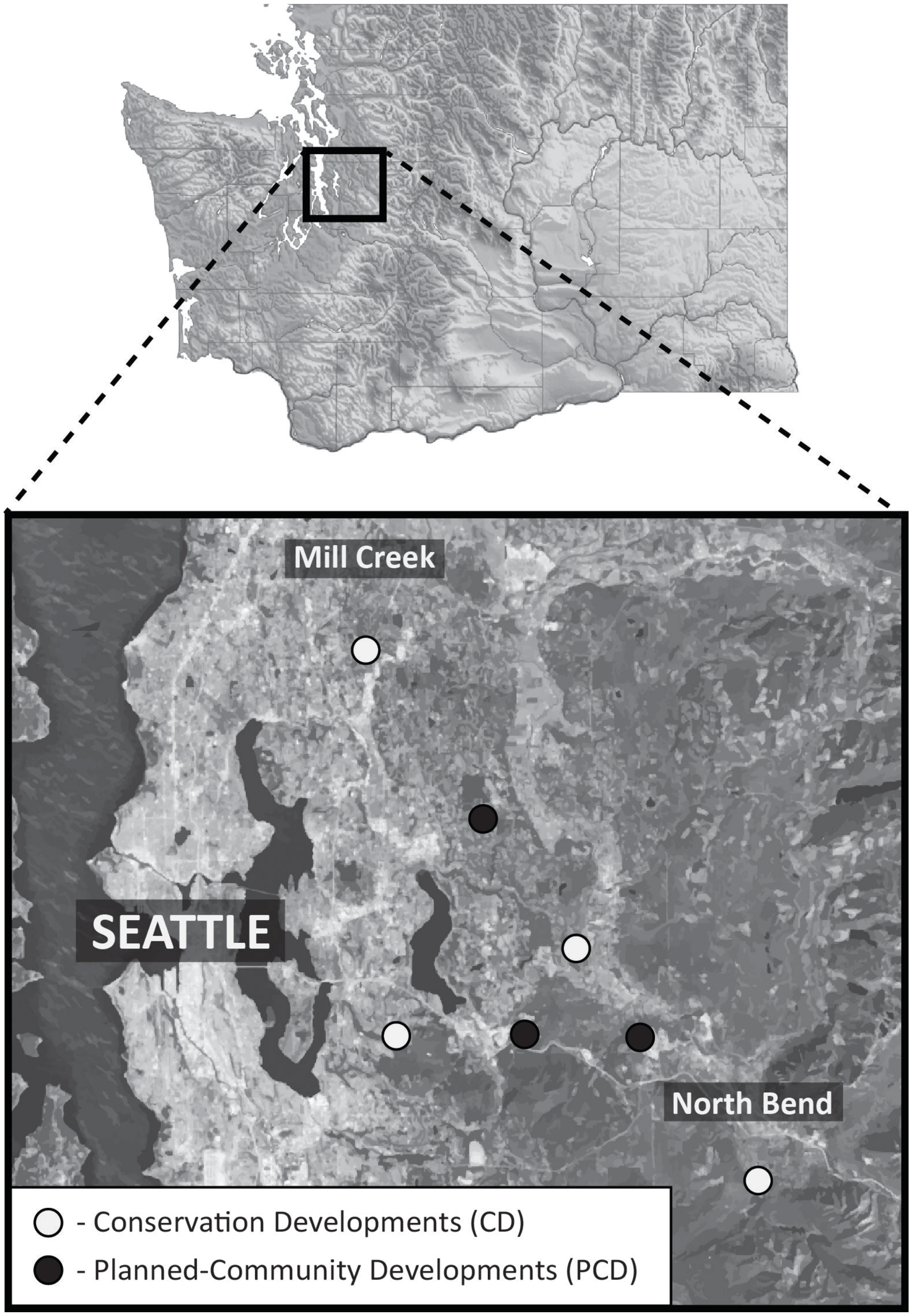

Figure 1. The study area (inset square) in Washington State (top) and again enlarged (bottom) indicating the location of two seven (7) sites (total) across two subtypes of actively changing residential housing communities; *Conservation Developments* (*CD, 4*) and *Planned Community Developments* (*PCD, 3*), evaluated for landscape change and monitored for avian community composition from 1998-2010.

3.5 RESULTS

3.5.1 *Prediction 1. All species (total) relative abundance by year: CD > PCD*

Contrary to prediction, CD sites did not support a greater number of birds (all species combined) than PCD sites (Fig.2). Rather, relative abundance tracked similarly in both development categories, increasing during early disturbance years (1-5), leveling off during intermediate years (6-10), and eventually falling (years 11-12). The best supported model for total species abundance included only year/time (delta AICc = 7.24 for next best model) as a quadratic function ($\beta_{time} + \beta_{time^2} = -0.063 \pm$ (SE) 0.015), (see Appendix 2.0 for full table of parameter values).

3.5.2 *Prediction 2. Relative abundance by Human-tolerance guild.*

3.5.2.1 2.a. Avoider species: Relative abundance of Avoider guild should be higher in CD than PCD with increasing time:

As anticipated, the relative abundance of Avoider species was greater in the CD sites than in PCD sites over time. Additionally, while Avoiders in CD sites increased during the intermediate years and ultimately decreased to initial levels by the study's end, Avoiders inhabiting PCD sites exhibited little to no increase. Instead, they declined in total abundance levels well below original values. The best model (delta AICc= 3.67 for next best model) included quadratic time effects and development type ($\beta_{time^2 \times CD} = -0.056 \pm$ (SE) 0.019); $t_{69.976} = -2.92$, $p = 0.005$) (see Appendix 2.0 for full table of parameter values).

3.5.2.2 2.b. Adaptor species: Relative abundance of Adaptor guild should be higher in CD than PCD with increasing time.

We found no meaningful differences in the total relative abundance of Adaptors between development types (CD, PCD), though collectively, this group demonstrated significant lasting gains throughout the study. The former result was not predicted, but the best model (delta AICc = 2.0) included a quadratic time trend ($\beta_{time^2} = -0.121 \pm$ (SE) 0.20), and a main effect of development type ($\beta_{devtype} = 0.605 \pm$ (SE) 0.843) (see Appendix 2.0 for full table of parameter values).

3.5.2.3 2.c. Exploiter species: Relative abundance of Exploiter guild should be higher in PCD than CD with increasing time.

Exploiters were more numerous in PCD sites than CD sites as expected. The full model performed best (delta AICc = 2.27), which included a quadratic time trend by development type ($\beta_{time^2 \text{ x CD}} = 0.045 \pm$ (SE) 0.021; $t_{70.107} = 2.12$ $p = 0.038$) (see Appendix 2.0 for full table of parameter values).

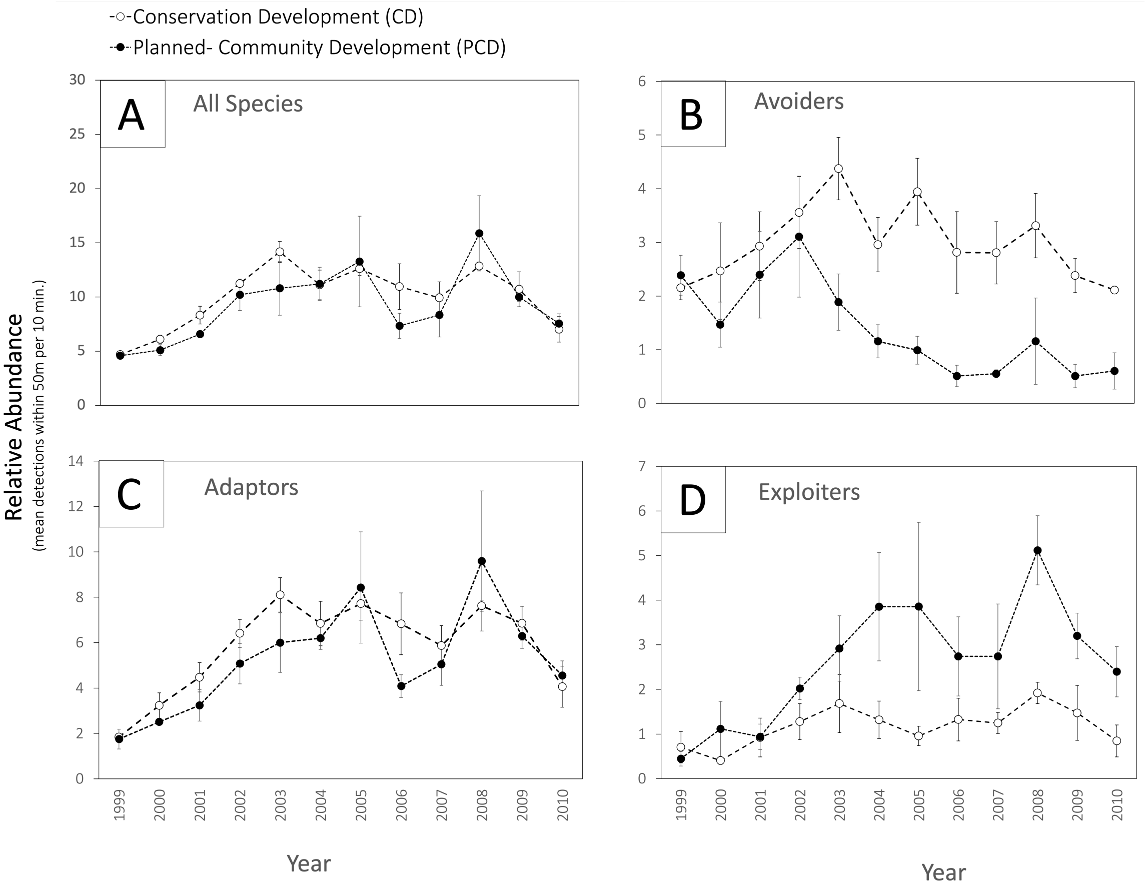

Figure 2. Relative abundance (average detections within 50m per 10-minute survey counts) ± SE (standard error), with y-axes scaled differently to illustrate trends more clearly of avian species combined (All Species) and by the human development tolerance guild (Avoiders, Adaptors, Exploiters) for two forms of 'new' residential development (Conservation, Planned Community) located in the Central Puget Lowlands of Washington State, 1999-2010.

3.5.3 *Prediction 3. Individual Species Performance by guild and development type*

3.5.3.1 3a. Representativeness of the local species pool

Most species populations (88.7%; 47/53) were relatively "stable" but highly variable during our twelve seasons of sampling, showing no definitive numerical increase or decrease in relative abundance by development type (see Appendix 3. Regression Analyses).

Of the species that showed apparent abundance differences by development type (11.3%; 6/53), proportionally the most were from the Exploiter guild (22.2%, 2 of 9 Exploiter species), followed by the Avoider species (16.7%, 3 of 18), and finally the Adaptor species (3.8%, 1 of 26). Within-guild performance profiles, based on the number of species demonstrating stable, increasing, quadratic, or decreasing abundance trends, were similar among categories (Table 1.).

Table 1. Species population (relative abundance) trends (stable, increasing, quadratic, decreasing) by guild and development type (All sites, Conservation Developments (CD), Planned-Community Developments (PCD). Table values tabulated by the guild (Avoider, Adaptor, Exploiter) based on statistical models for each species' performance by landscape development categories and guild membership (see Appendix 3. Regression Analyses) with parenthetic values denoting the number of species represented.

Population Trend (Relative Abundance over Time)	**Landscape Development Type**	**SPECIES PERFORMANCE WITHIN GUILD**		
		Avoider (18)	**Adapter** (26)	**Exploiter** (9)
Stable*	All Sites	72.2% (13)	53.8% (14)	55.5% (5)
	CD	0%	0% (0)	11% % (1)
	PCD	0%	0% (0)	0% (0)
Increasing	All Sites	5.6% (1)	26.9% (7)	22.2% (2)
	CD	16.7% (3)	0% (0)	0% (0)
	PCD	0% (0)	3.8% (1)	11.1% (1)
Quadratic	All Sites	0% (0)	15.4% (4)	22.2% (2)
	CD	5.6% (1)	0 % (0)	0% (0)
	PCD	0% (0)	0% (0)	11.1% (1)
Decreasing	All Sites	5.6% (1)	15.4% (4)	11.1% (1)
	CD	0% (0)	0% (0)	0% (0)
	PCD	5.6% (1)	0% (0)	0% (0)

*Stable: Conservatively defined as NOT significantly increasing or decreasing, which can result from either low or extremely high longitudinal variability

3.5.3.2 3.b Avoiders: Species-specific responses

Within the Avoider guild, four species emerged with clearly changing (increasing or decreasing) populations during the study period (Table 1.). Both Chestnut-backed Chickadee (*Poecile rufescens*) and Swainson's Thrush (*Catharus ustulatus*) were clear 'winners' in the CD sites (Figure 2). The most abundant of these two, the Chestnut-backed Chickadee, showed a substantial increase in abundance through time (See Appendix 3., Individual Species Regression Analyses) at CD sites. In contrast, their abundance was relatively flat year-over-year at the PCD sites (Figure 2). Contrastingly, Swainson's Thrush increased in the CD sites but decreased in the PCD sites over the twelve years. Several species responded to the habitat changes irrespective of housing density. For instance, the Red-breasted Sapsucker (*Sphyrapicus ruber*) was the only species to increase in number, while the Pacific Wren (*Troglodytes pacificus*) declined in abundance across both landscape categories (Figure 2).

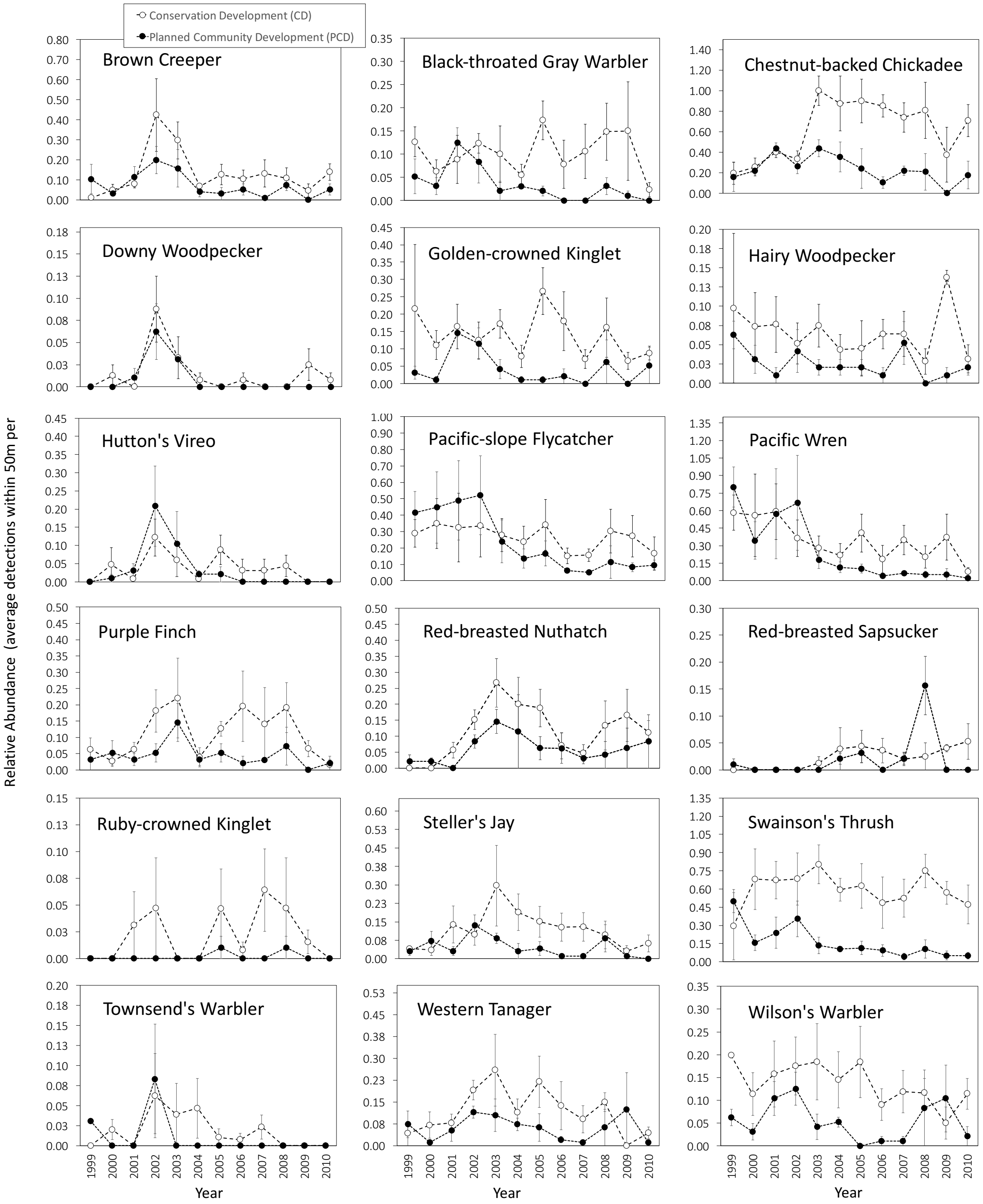

Figure 2. Relative abundance (average detections within 50m per 10-minute survey counts) ± SE (standard error), with y-axes scaled differently to illustrate trends more clearly, of individual 'Avoider' guild species for two forms of 'new' residential development (Conservation, Planned Community) located in the Central Puget Lowlands of Washington State, 1999-2010.

3.5.3.3 3.c. Adaptors: Species-specific responses

Adaptor species responses were equivocal to development type among the three human development tolerance guilds (Table 1). No Adaptor species increased in abundance in the CD sites alone, and only the White-crowned Sparrow (*Zonotrichia leucophrys*) grew in abundance in higher-density PCD sites (Figure 4). Instead, roughly a quarter (26.9%, 7/26) of the guild's species increased in both CD and PCD sites (Table 1). This group of seven species included American Goldfinch (*Spinus tristis*), Bushtit (*Psaltriparus minimus*), Dark-eyed Junco (*Junco hyemalis*), Evening Grosbeak (*Coccothraustes vespertinus*), Savannah Sparrow (*Passerculus sandwichensis*), and Warbling Vireo (*Vireo gilvus*). Four species (15.4%) represented the guild's members exhibiting declining populations through time (Table 1). All examples in this group, Cedar Waxwings (*Bombycilla cedrorum*), Pine Siskins (*Spinus pinus*), Song Sparrows (*Melospiza melodia*), and Violet-green Swallows (*Tachycineta thalassina*), experienced quadratic population trajectories that suggest initial increases are followed by declines below values at the start of the study (Figures 3. & 4.).

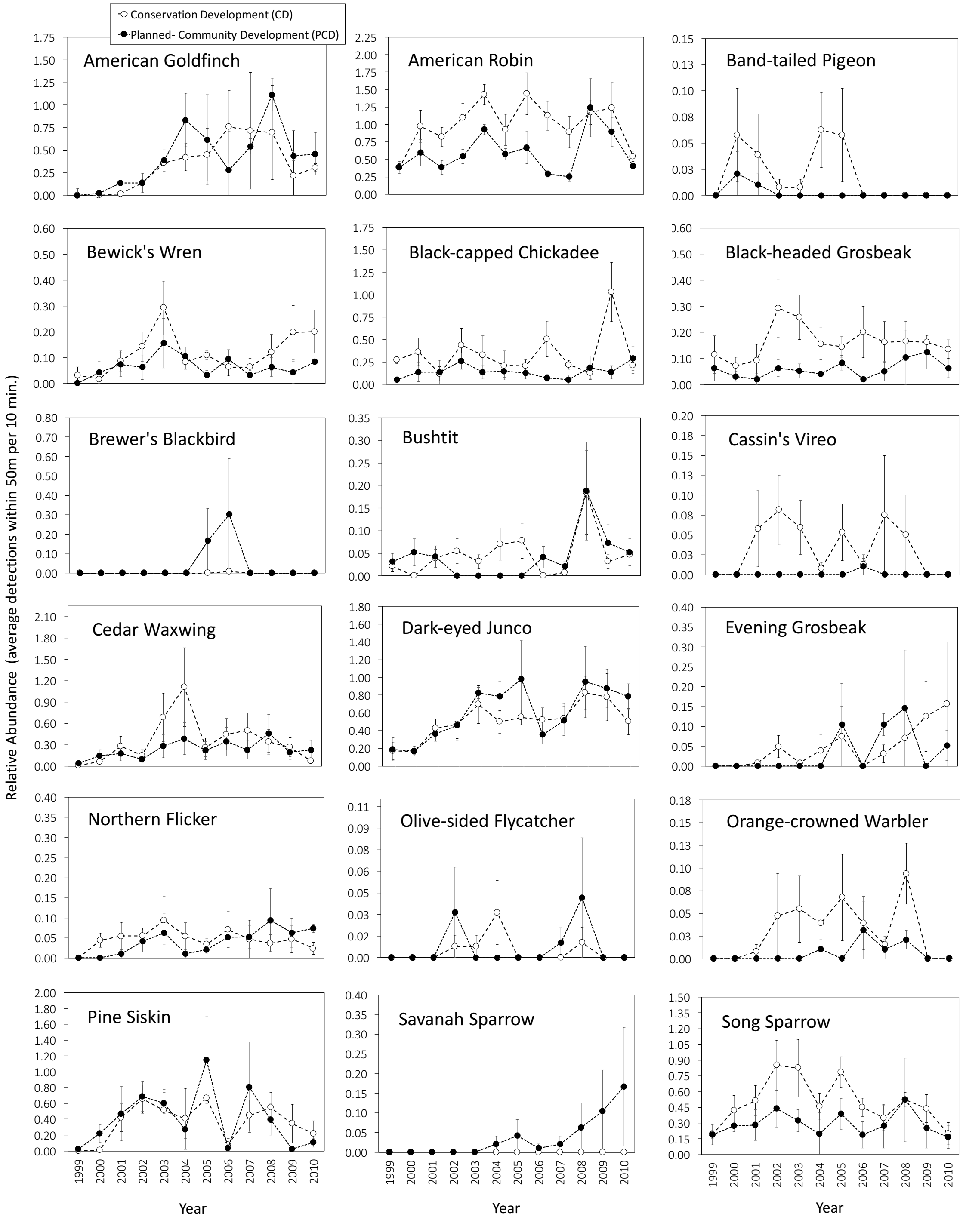

Figure 3. Relative abundance (average detections within 50m per 10-minute survey counts) ± SE (standard error), with y-axes scaled differently to illustrate trends more clearly, of individual 'adaptor' guild (species 1-18) for two forms of 'new' residential development (Conservation, Planned Community) located in the Central Puget Lowlands of Washington State, 1999-2010.

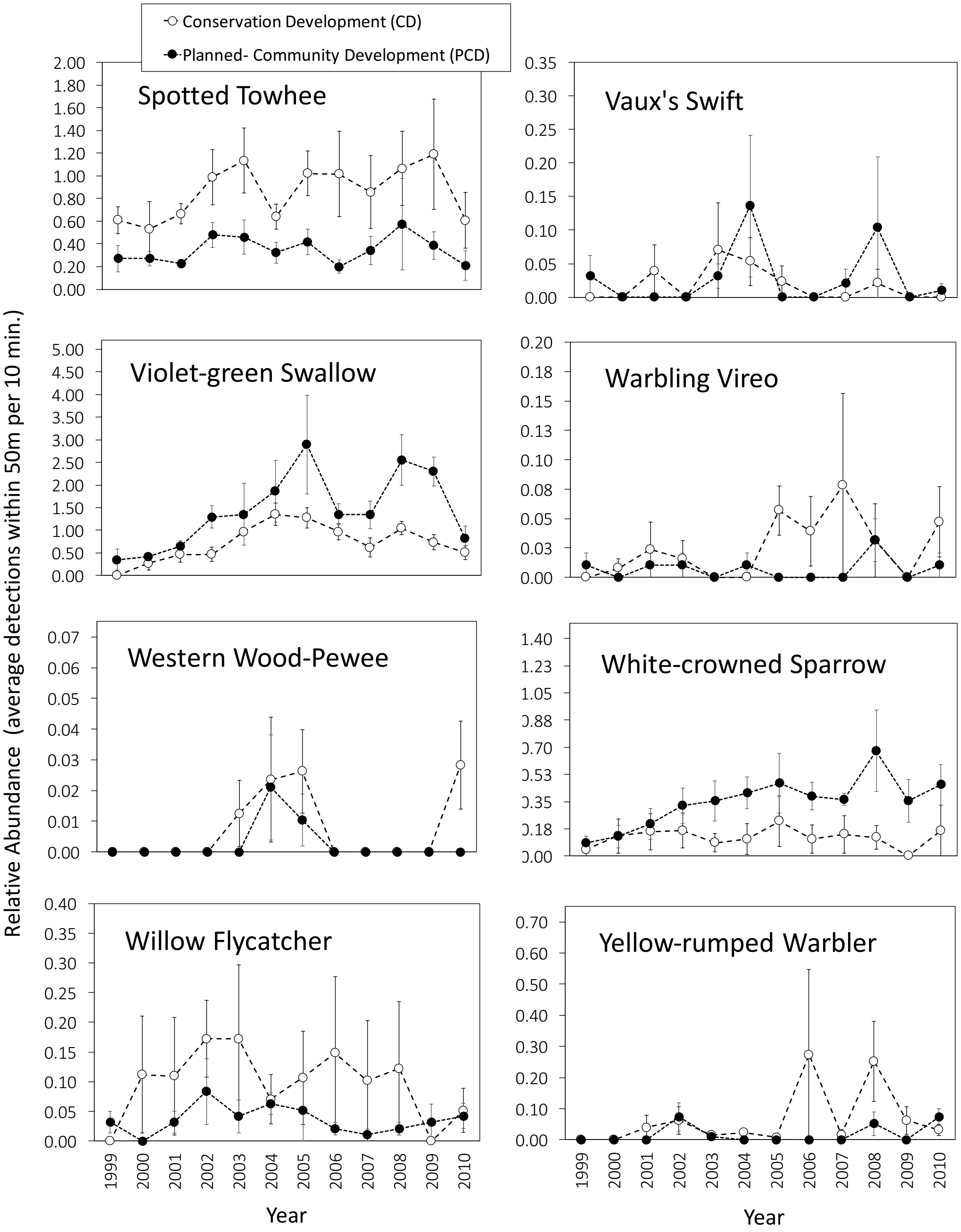

Figure 4. Relative abundance (average detections within 50m per 10-minute survey counts) ± SE (standard error), with y-axes scaled differently to illustrate trends more clearly of individual 'Adaptor' guild (species 19-26) for two forms of 'new' residential development (Conservation, Planned Community) located in the Central Puget Lowlands of Washington State, 1999-2010.

3.5.3.4 3.d. Exploiters: Species-specific responses

Exploiter species performed similarly to Adapters in overall temporal stability and specificity for increasing, quadratic and decreasing populations through time (Table 1, Figure 5). Roughly half of all Exploiter species (55.5%, 5/9) were constant in number across all sites through the study, including Anna's (*Calypte ann*a) and Rufous Hummingbirds (*Selasphorus rufus*), Barn Swallows (*Hirundo rustica*), House Finches (*Haemorhous mexicanus*) and House Sparrows (*Passer domestic*us). While House Sparrow relative abundance was highly variable among PCD sites, showing no directional trend over time, this species essentially failed to colonize CD sites during the study. Two species demonstrated linear increases through time irrespective of development type, American Crows (*Corvus brachyrhynchos*) and Rock Pigeons (*Columba livia*). Two species in the Exploiter category exhibited quadratic trends; European Starlings (*Sturnus vulgaris*) showed clear gains in the PCD sites compared to CD sites, while Brown-headed Cowbirds (*Molothrus ater*) were insensitive to development type. No Exploiter species revealed linear population decreases.

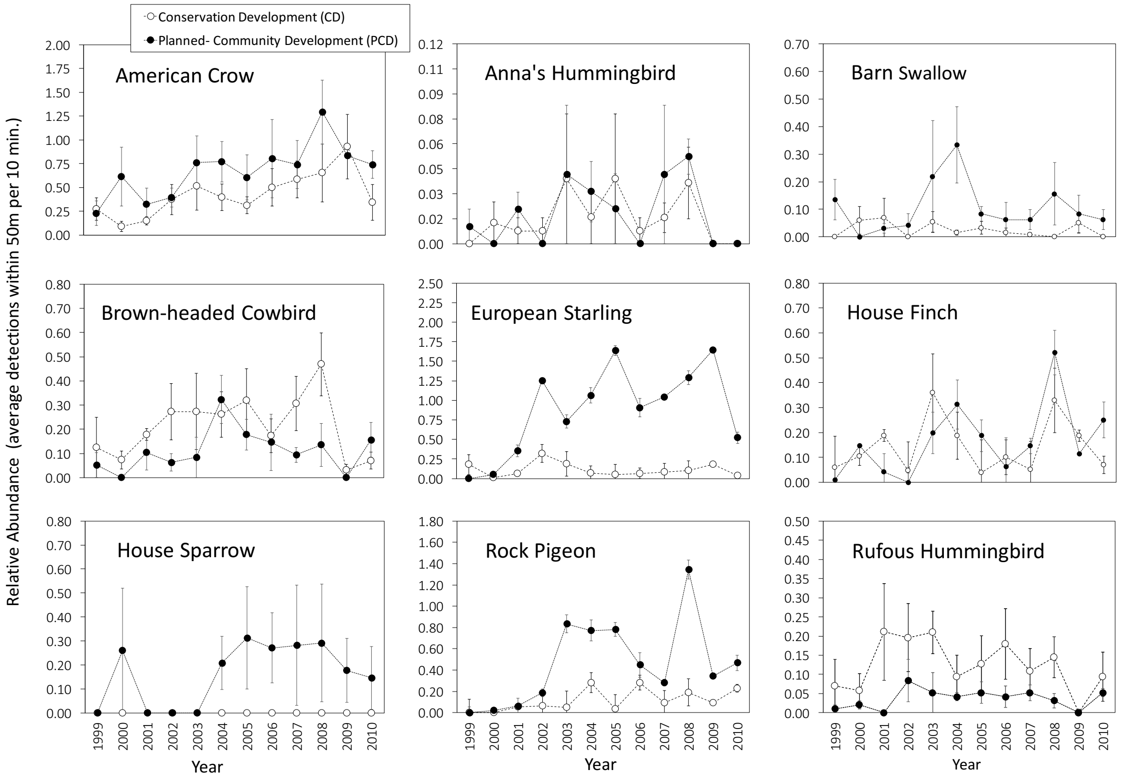

Figure 5. Relative abundance (average detections within 50m per 10-minute survey counts) ± SE (standard error), with y-axes scaled differently to illustrate trends more clearly, of individual 'Exploiter' guild species for two forms of 'new' residential development (Conservation, Planned Community) located in the Puget Lowlands of Western Washington State, 1999-2010.

3.6 DISCUSSION

Residential development modifies local landscapes, resulting in alterations to bird assemblages (Blair 1996, 1999, Melles et al. 2003b, Hansen et al. 2005b, Marzluff et al. 2007, Ford and Flaspohler 2010, Farwell and Marzluff 2013, Shryock and Marzluff 2014, Marzluff et al. 2015, Marzluff et al. 2016, DeLap 2022). Less is known, however, about bird communities inhabiting converting landscapes. Similarly, less is known about responses across variable subdivision types, although studies of species richness and dominance have revealed meaningful fine-grain relationships (Farr et al. 2017, Battisti 2018). Comparisons of breeding birds in different development intensities highlight the challenges to conserving representative species facing such widespread landscape modification (Melles et al. 2003a, Donnelly and Marzluff 2004, Mckinney 2006, Devictor et al. 2007, Palomino and Carrascal 2007, Blair and Johnson 2008, Lepczyk et al. 2008, Shustack and Rodewald 2008, Lepczyk et al. 2017, James Reynolds et al. 2019).

3.6.1 *Abundance*

Past research (Palomino and Carrascal 2007) shows increased avian community abundance (following conversion of native vegetation to development), likely responding to the increased heterogeneity of habitat (Tratalos et al. 2007). However, this finding is not consistent among all studies (Geschke et al. 2018). Overall bird abundance increased similarly in both development types during this study, primarily predicted by urbanization gradient analyses in this study area (Marzluff et al. 2015) and elsewhere (Blair 1996, Chace and Walsh 2006, Palomino and Carrascal 2006). In general, as habitat becomes more heterogeneous, so too does avian species diversity increases (Blair and Johnson 2008, Marzluff et al. 2015) often accompanied by increased breeding territory densification (Yeh 2004, Blair and Johnson 2008) and thus a rise in the total population of birds occupying the landscape.

3.6.2 *Human Development Tolerance Guilds*

Framing bird community change by the response of human development tolerance guilds has proven insightful in past research (Blair 1999, Blair and Johnson 2008, Geschke et al. 2018). Generally, CDs maintained Avoider species and excluded Exploiters. Avoiders likely benefit from greater remnant forest in conservation developments (Chace and Walsh 2006, Merenlender et al. 2009). Initial increases in Avoider abundance may result from these forest obligate/adapted species crowding into the persisting forest patches in the aftermath of fragmentation (Schmiegelow et al. 1997, Whittaker and Marzluff 2009, Marzluff et al. 2016). Later declines could result from human activity (DeLap 2022) and insufficient adaptation to the shifting nest predator community (Marzluff et al. 2016).

Adaptor species may colonize newly emerging habitats evenly across residential development types when the degree of fragmentation is similar (Lowry et al. 2013). Removal of forest leads to increased bare earth and grass areas, providing foraging opportunities for several early successional ground and shrub-feeding bird species (Blair 1996, Mckinney 2006, Marzluff et al. 2015). Exploiters benefit from habitat augmented with built land cover (Blair 1996, Marzluff et al. 2015, Geschke et al. 2018). For instance, artificial nest substrates associated with human structures can lead to high nest success (Marzluff et al. 2015), despite likely increases in locally subsidized predators, both native (corvids, opossums, raccoons), and non-native (introduced rats, domestic cats) (Nilon et al. 1995, Gering and Blair 1999, Malpass et al. 2018). High nest success coupled with an abundance of anthropogenic food resources (bird feeders, pet food, vegetable gardens, ornamental fruit trees, and shrubs) likely translate into elevated survival rates for juvenile and adult Exploiters (Marzluff et al. 2015).

3.6.3 *Species-specific Responses*

Research is limited on the ability of avian guilds ranked by human development tolerance to characterize species-level population dynamics (Battisti 2018, Villasenor et al. 2021). Among Avoiders, only 2 of the 18 guild species demonstrated slight (Swainson's Thrush) to modest (Chestnut-backed Chickadee) gains in relative abundance when occupying the lower intensity residential developments. Swainson's Thrush, while not remarkably tolerant of human activity (Marzluff et al. 2016), may benefit from increased forest edge habitat conducive to native fruiting shrubs, such as huckleberry (*Vaccinium* sp.) and Salmonberry (*Rubus spectabilis*), often selected for both nesting and foraging (Mack and Yong 2000, Shirley 2005). Chestnut-backed Chickadees were among the species with slighter higher nest success in these changing landscapes relative to forest reserves (Marzluff et al. 2015); the key would be those sites maintaining naturally occurring snags for these secondary cavity nesters while still providing elevated foraging opportunities (Blewett and Marzluff 2005).

The relative abundance of the remaining Avoider species exhibited high year-over-year variability, indicative of species subjected to the destabilizing effects of landscape change (Devictor et al. 2007, DeLap 2022). A few specialist species, Pacific Wrens and Pacific-slope Flycatchers, for instance, declined in numbers across residential development intensities (Blair 1996). Specific decreases in reproductive success established in earlier analyses of the study area (Marzluff et al. 2015) could result from fragmentation-fueled vulnerability to nest predation, indicated by Pacific-slope flycatchers' negative association with increasing numbers of American Crows (Marzluff et al. 2007). We know of multiple urbanization factors negatively impacting Pacific Wren populations, including reduced survival and increased emigration in the wake of forest removal (Marzluff et al. 2016) and aggression from colonizing Bewick's wrens (Farwell and Marzluff 2013) Adaptors, often the most speciose of the human development tolerance guilds, are consistently dominated by a few species. Often these species, including sparrows and finches, are granivorous, an advantage in urbanizing settings accompanied by increased grass seed and bird feeders (Fraterrigo and Wiens 2005, Chace and Walsh 2006, Blair and Johnson 2008, Evans et al. 2009, Van Rensburg et al. 2009). Aerial insectivore populations (e.g., Violet-green Swallows) profit from landscapes with less vertical structure, foraging amidst expanding meadow-like habitats, and newly created sources of open water such as subdivision retention ponds (DeLap 2022). While many secondary cavity-nesting species are limited by natural cavities (Blewett and Marzluff 2005), Violet-green Swallow numbers did not correlate with forest cover (Tomasevic and Marzluff 2017) but readily used anthropogenic structures (e.g., houses, street lamps, etc.).

A few highly successful species consistently dominate the Exploiter guild (Mckinney 2006, Devictor et al. 2007, Marzluff et al. 2008, Pickett et al. 2011). Populations of non-native species, such as European Starlings and Rock Pigeons, are supplemented by anthropogenic foraging opportunities – including bird feeders, lawns, and gardens – and nesting sites (Blair 1996, Gering and Blair 1999, Marzluff et al. 2001, Miller et al. 2003, Fraterrigo and Wiens 2005, Hansen et al. 2005b, Newson et al. 2008, Farr et al. 2017). Native corvid populations (e.g., American Crow and Steller's Jay) may exploit human subsidies and prey on localized songbird nests. Still, they did not diminish passerines' relative abundance or reproductive success in our study area (Marzluff et al. 2007, Marzluff et al. 2015) as found elsewhere (Miller et al. 2003, Xu et al. 2020).

3.6.4 *Conservation Considerations*

This study further demonstrates that the pattern of development (housing density and remaining vegetation amount and arrangement) has the potential to both boost species diversity in moderately disturbed areas (Connell 1978; Blair 1996, 2004; Marzluff 2005, Marzluff 2015) and minimize biotic homogenization compared to the very dense developments in nearby urban areas (Donnelly and Marzluff 2004, Chapman and Reich 2007, Blair and Johnson 2008, Lin and Fuller 2013, Geschke et al. 2018, Malpass et al. 2018). Diverse urban bird communities benefit local ecologies (Colding 2007), though more work is needed for human residents to appreciate the ecosystem services they provide fully (Tilt and Cerveny 2013, Clucas et al. 2015)

Land cover and land use change are inevitable with urbanization. Consequently, continued monitoring of avian communities is needed to evaluate ecological processes that may lead to an extinction debt or the temporary delay in loss of species following environmental change over time (Warren et al. 2019). We did not document localized species extinction from our study sites, though Pacific Wren numbers declined the most. Source-sink dynamics (Pulliam and Danielson 1991, Hansen and Rotella 2002, Alberti 2005) may sustain continued specialist species presence through crosspatch movement. We expect the abundance of Exploiter species to increase through time and Avoiders to decrease as existing developments mature. With biotic homogenization a possibility, the struggle for regional avian diversity centers on two fronts 1) temporal landscape conversion, the amount of area experiencing change at any given time, and 2) the resulting cumulative habitat quality and arrangement yet to be affected in the remaining undeveloped/least developed landscape category (Alberti 2005, Hepinstall et al. 2008).

While physical composition and structure alterations are critical considerations, additional anthropogenic factors present possible mechanisms for future bird community change. Human movements, both routine and recreational, variably stress species, altering when and where individuals will forage and nest (Steven et al. 2011). Likewise, domestic animals, namely cats and, to a lesser extent, dogs, present existential threats to some birds (Loss et al. 2013). Noise pollution can alter avian vocal communication (Slabbekoorn 2013). Artificial light sources may disrupt songbirds directly (Xue et al. 2020) as well as nocturnal avian and mammalian nest predator communities (Newport et al. 2014). Avian mortality resulting from collisions with anthropogenic features is significant (Loss et al. 2015). Window strikes take a toll on some species (Basilio et al. 2020), and the prevalence of windows may increase post development, making matters worse for birds. However, technologies such as ultra-violet light reflecting applications could help. The frequency of bird collisions with automobiles (Loss et al. 2014) may also shift, gaining in severity when traffic rises or possibly falls with the adoption of alternative transportation means and corridors. While this suite of human presence-related variables may positively correlate with development density, additional research is needed to determine if and which species are most affected. Lastly, seasonality (e.g., winter survival of resident species) and climate change (e.g., future deviations in temperature, precipitation, phenology, and vegetation composition and configuration) are critical facets of the suburban-urban bird community change that require increased conservation attention (Jongsomjit et al. 2013, Berthon et al. 2021).

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3.8 APPENDIX A. AVIAN SPECIES LIST

Species listed by human development tolerance guild; 53 species total used for analyses.

Synanthropic Guild (Species Number)	**Common Name**	**Scientific Name**
Avoiders (18)	Brown Creeper	*Certhia americana*
	Black-throated Gray Warbler	*Setophaga nigrescens*
	Chestnut-backed Chickadee	*Poecile rufescens*
	Downy Woodpecker	*Picoides pubescens*
	Golden-crowned Kinglet	*Regulus satrapa*
	Hairy Woodpecker	*Picoides villosus*
	Hutton's Vireo	*Vireo huttoni*
	Pacific-slope Flycatcher	*Empidonax difficilis*
	Pacific Wren	*Troglodytes pacificus*
	Purple Finch	*Haemorhous purpureus*
	Red-breasted Nuthatch	*Sitta canadensis*
	Red-bellied Sapsucker	*Sphyrapicus ruber*
	Ruby-crowned Kinglet	*Regulus calendula*
	Steller's Jay	*Cyanocitta stelleri*
	Swainson's Thrush	*Catharus ustulatus*
	Townsend's Warbler	*Setophaga townsendi*
	Western Tanager	*Piranga ludoviciana*
	Wilson's Warbler	*Cardellina pusilla*
Adapters (26)	American Goldfinch	*Spinus tristis*
	American Robin	*Turdus migratorius*
	Band-tailed Pigeon	*Patagioenas fasciata*
	Bewick's Wren	*Thryomanes bewickii*
	Black-capped Chickadee	*Poecile atricapillus*
	Black-headed Grosbeak	*Pheucticus melanocephalus*
	Brewer's Blackbird	*Euphagus cyanocephalus*
	Bushtit	*Psaltriparus minimus*
	Cassin's Vireo	*Vireo cassinii*
	Cedar Waxwing	*Bombycilla cedrorum*
	Dark-eyed Junco	*Junco hyemalis*
	Evening Grosbeak	*Coccothraustes vespertinus*
	Northern Flicker	*Colaptes auratus*
	Olive-sided Flycatcher	*Contopus cooperi*
	Orange-crowned Warbler	*Oreothlypis celata*
	Pine Siskin	*Spinus pinus*
	Savannah Sparrow	*Passerculus sandwichensis*
	Song Sparrow	*Melospiza melodia*
	Spotted Towhee	*Pipilo maculatus*
	Vaux's Swift	*Chaetura vauxi*
	Violet-green Swallow	*Tachycineta thalassina*
	Warbling Vireo	*Vireo gilvus*
	White-crowned Sparrow	*Zonotrichia leucophrys*
	Western Wood-Pewee	*Contopus sordidulus*
	Willow Flycatcher	*Empidonax traillii*
	Yellow-rumped Warbler	*Setophaga coronata*
Exploiters (9)	American Crow	*Corvus brachyrhynchos*
	Anna's Hummingbird	*Calypte anna*
	Barn Swallow	*Hirundo rustica*
	Brown-headed Cowbird	*Molothrus ater*
	European Starling	*Sturnus vulgaris*
	House Finch	*Haemorhous mexicanus*
	House Sparrow	*Passer domesticus*
	Rock Pigeon	*Columba livia*
	Rufous Hummingbird	*Selasphorus rufus*

3.9 APPENDIX B. STATISTICAL MODELING

3.9.1 *Analyses by Guild*

Parameters for best (AICc model selection) linear mixed-effects model analyses for relative abundance of avian community (all species) and human-tolerance guild (Avoiders, Adaptors, Exploiters).

3.9.1.1 All Species (combined)

Parameter (β)	Estimate	Std. Error	df	t	*p*-value	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	0.545	0.574	240	0.949	0.344	-0.586	1.675
Time	0.936	0.201	240	4.658	0.000	0.540	1.332
$Time^2$	-0.063	0.015	240	-4.204	0.000	-0.093	-0.034

Dependent Variable: Relative abundance (average detections within 50m per 10-minute survey for each site in each breeding season/year).

3.9.1.2 Avoiders

Parameter (β)	Estimate	Std. Error	df	t	*p*-value	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	2.701	0.681	23.610	3.966	0.001	1.294	4.108
CD	-1.307	0.921	25.277	-1.419	0.168	-3.203	0.589
PCD	0^a	0.000	.	.	.	.	.
Time	-0.223	0.190	69.890	-1.177	0.243	-0.602	0.155
$Time^2$	0.003	0.014	69.890	0.188	0.851	-0.026	0.031
CD*Time	0.910	0.258	69.978	3.531	0.001	0.396	1.423
PCD*Time	0^a	0.000	.	.	.	.	.
CD* $Time^2$	-0.056	0.019	69.976	-2.921	0.005	-0.095	-0.018
PCD * $Time^2$	0^a	0.000	.	.	.	.	.

Dependent Variable: Relative abundance (average detections within 50m per 10-minute survey for each site in each breeding season/year).

a This parameter is set to zero because it is redundant.

3.9.1.3 Adaptors

Parameter (β)	Estimate	Std. Error	df	t	*p*-value	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	-0.380767	0.958592	22.882	-0.397	0.695	-2.364331	1.602798
Time	1.8723	0.263556	72.209	7.104	0.000	1.346936	2.397663
Time2	-0.121062	0.01969	72.204	-6.148	0.000	-0.160312	-0.081813
CD/PCD	0.605173	0.842843	4.967	0.718	0.505	-1.565765	2.776111

Dependent Variable: Relative abundance (average detections within 50m per 10-minute survey for each site in each breeding season/year).

3.9.1.4 Exploiters

Parameter (β)	Estimate	Std. Error	df	t	*p*-value	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	-0.888742	0.702021	31.822	-1.266	0.215	-2.319026	0.541541
CD	1.224144	0.95175	33.965	1.286	0.207	-0.71012	3.158407
Time	1.047505	0.207745	69.994	5.042	0.000	0.63317	1.461839
Time^2	-0.061076	0.015557	69.994	-3.926	0.000	-0.092102	-0.030049
CD* Time	-0.779531	0.281993	70.111	-2.764	0.007	-1.341932	-0.21713
CD* Time^2	0.044685	0.021075	70.107	2.12	0.038	0.002654	0.086717

3.9.2 *Individual Species Regression Analysis*

3.9.2.1 Avoider Guild Member Species

Linear mixed effects regression analyses for avian Avoider species as determined by AICc ranking (Burnham & Anderson 1998) four candidate models: linear time, quadratic time, linear time by development site type (Conservation Development or Planned Community Development) and quadratic time by development site type for study in Puget Sound Lowlands, 1999-2010.

Species	Best Model * = signifcant @ α = 0.05, excluding intercept	Next Best Model	Δ AICc	Parameter (β) * = signifcant @ α = 0.05	Estimate	Std. Error	df	t	*p* -value	95% Confidence Interval	
										Lower Bound	Upper Bound
Brown creeper	Time	Time2	7.853	Intercept	0.143	0.040	42.143	3.552	0.001	0.062	0.224
				time	-0.005	0.004	73.192	-1.049	0.298	-0.013	0.004
Black-throated gray warbler	Time	Time x SiteType	8.344	Intercept	0.094	0.026	14.858	3.539	0.003	0.037	0.150
				time	-0.003	0.002	73.009	-1.368	0.175	-0.007	0.001
Chestnut-backed chickadee	*Time2 x SiteType	Time x SiteType	4.079	Intercept	0.133	0.219	51.722	0.609	0.545	-0.306	0.573
				time	0.059	0.059	69.944	1.006	0.318	-0.058	0.177
				*[site_type=CD]	-0.630	0.298	53.935	-2.117	0.039	-1.227	-0.033
				*[site_type=CD] * time	0.249	0.080	70.058	3.109	0.003	0.089	0.408
				time2	-0.005	0.004	69.944	-1.310	0.195	-0.013	0.003
				*[site_type=CD] * time2	-0.012	0.005	70.054	-2.389	0.020	-0.023	-0.002
Downy woodpecker	Time	TIME 2	12.284	Intercept	0.004	0.017	78.000	0.257	0.798	-0.029	0.037
				time	0.005	0.005	78.000	1.039	0.302	-0.005	0.015
				time2	0.000	0.000	78.000	-1.405	0.164	-0.001	0.000
Golden-crowned kinglet	Time	TIME 2	11.743	Intercept	0.134	0.037	16.635	3.634	0.002	0.056	0.212
				time	-0.004	0.003	72.982	-1.385	0.170	-0.011	0.002
Hairy woodpecker	Time	Time x SiteType	12.383	Intercept	0.065	0.016	27.129	3.996	0.000	0.031	0.098
				time	-0.003	0.002	73.072	-1.597	0.114	-0.006	0.001
Hutton's vireo			5.975	Intercept	0.063	0.022	27.651	2.866	0.008	0.018	0.109
				time	-0.004	0.002	72.968	-1.615	0.111	-0.008	0.001
Pacific-slope flycatcher	*Time		2.305	Intercept	0.450	0.076	12.523	5.884	0.000	0.284	0.616
				*time	-0.027	0.006	73.044	-4.701	0.000	-0.038	-0.016
		*Time x SiteType		Intercept	0.558	0.122	8.747	4.578	0.001	0.281	0.835
				time	-0.043	0.008	72.009	-5.310	0.000	-0.059	-0.027
				[site_type=CD]	-0.201	0.162	8.996	-1.239	0.247	-0.569	0.166
				[site_type=CD] * time	0.030	0.011	72.026	2.700	0.009	0.008	0.052
Pacific wren	*Time	Time x SiteType	5.671	Intercept	0.670	0.095	20.422	7.013	0.000	0.471	0.869
				*time	-0.050	0.009	73.051	-5.622	0.000	-0.067	-0.032
Purple finch	Time	Time 2	4.004	Intercept	0.080	0.038	14.708	2.113	0.052	-0.001	0.161
				time	0.001	0.003	72.988	0.238	0.813	-0.005	0.007
Red-breasted nuthatch	Time		2.259	Intercept	0.057	0.032	27.287	1.770	0.088	-0.009	0.123
				time	0.005	0.003	73.191	1.428	0.158	-0.002	0.011
		*Time 2		Intercept	-0.085	0.054	71.297	-1.572	0.120	-0.194	0.023
				*time	0.052	0.015	72.342	3.448	0.001	0.022	0.082
				*time2	-0.003	0.001	72.344	-3.209	0.002	-0.005	-0.001
Red-breasted sapsucker	*Time	Time 2	13.127	Intercept	-0.011	0.012	52.052	-0.889	0.378	-0.034	0.013
				*time	0.004	0.001	73.001	3.085	0.003	0.001	0.007
Ruby-crowned kinglet	Time	Time 2	12.513	Intercept	0.007	0.012	45.194	0.595	0.555	-0.016	0.030
				time	0.001	0.001	72.557	0.689	0.493	-0.002	0.004
Steller's jay	Time			Intercept	0.106	0.038	15.632	2.781	0.014	0.025	0.187
				time	-0.002	0.003	72.986	-0.710	0.480	-0.009	0.004
		*Time 2	1.541	Intercept	-0.041	0.058	51.815	-0.707	0.483	-0.156	0.075
				time	0.047	0.015	72.082	3.116	0.003	0.017	0.077
				time2	-0.003	0.001	72.083	-3.335	0.001	-0.005	-0.001
Swainson's thrush	*Time x SiteType		0.915	*Intercept	0.385	0.144	9.391	2.677	0.024	0.062	0.709
				*time	-0.030	0.010	71.969	-2.932	0.005	-0.050	-0.010
				[site_type=CD]	0.223	0.192	9.688	1.161	0.274	-0.207	0.652
				*[site_type=CD] * time	0.028	0.014	71.989	2.057	0.043	0.001	0.056
		Time		*Intercept	0.518	0.126	8.782	4.127	0.003	0.233	0.803
				*time	-0.014	0.007	73.018	-2.044	0.045	-0.028	0.000
Townsend's warbler	Time	Time 2	12.155	Intercept	0.031	0.012	47.405	2.649	0.011	0.008	0.055
				time	-0.002	0.001	72.995	-1.640	0.105	-0.005	0.000
Western tanager	Time		2.122	*Intercept	0.105	0.035	19.604	2.965	0.008	0.031	0.179
				time	-0.001	0.003	72.977	-0.392	0.696	-0.008	0.005
		*Time 2		Intercept	-0.039	0.056	61.715	-0.696	0.489	-0.152	0.074
				*time	0.047	0.015	72.102	3.083	0.003	0.017	0.077
				*time2	-0.003	0.001	72.104	-3.231	0.002	-0.005	-0.001
Wilson's warbler	Time	Time x SiteType	7.192	Intercept	0.139	0.030	19.907	4.563	0.000	0.075	0.202
				time	-0.005	0.003	73.008	-1.686	0.096	-0.010	0.001

3.9.2.2 Adaptor Guild Member Species

Linear mixed effects regression analyses for avian Adaptor species as determined by AICc ranking (Burnham & Anderson 1998) four candidate models: linear time, quadratic time, linear time by development site type (Conservation Development or Planned Community Development) and quadratic time by development site type for study in Puget Sound Lowlands, 1999-2010.

Species	Best Model * = signifcant @ α =0.05, excluding	Next Best Model	Δ AICc	Parameter (β) * = signifcant @ α =0.05	Estimate	Std. Error	df	t	*p* -value	95% Confidence Interval	
										Lower Bound	Upper Bound
American goldfinch	*Time	*Time ^{2}	3.514	Intercept	-0.022	0.181	12.485	-0.119	0.907	-0.415	0.371
				*Time	0.056	0.014	72.926	4.065	0.000	0.028	0.083
American robin	Time		0.350	Intercept	0.726	0.150	16.631	4.838	0.000	0.409	1.043
				Time	0.015	0.013	72.986	1.137	0.259	-0.011	0.041
		*Time ^{2}		Intercept	0.178	0.231	57.467	0.774	0.442	-0.283	0.640
				Time	0.197	0.061	72.099	3.223	0.002	0.075	0.320
				Time2	-0.012	0.004	72.101	-3.045	0.003	-0.020	-0.004
Band-tailed pigeon	Time	Time ^{2}	13.461	Intercept	0.030	0.012	27.938	2.616	0.014	0.007	0.054
				Time	-0.002	0.001	72.707	-1.912	0.060	-0.005	0.000
Bewick's wren	Time		10.584	Intercept	0.055	0.031	31.679	1.767	0.087	-0.008	0.118
				Time	0.005	0.003	73.220	1.586	0.117	-0.001	0.012
Black-capped chickadee	Time	Time x SiteType	7.194	Intercept	0.190	0.083	20.309	2.281	0.033	0.016	0.363
				Time	0.006	0.008	73.117	0.748	0.457	-0.010	0.021
Black-headed grosbeak	Time	Time 2	10.526	Intercept	0.092	0.042	12.086	2.208	0.047	0.001	0.183
				Time	0.004	0.003	72.990	1.273	0.207	-0.002	0.010
Brewer's blackbird	Time	Time 2	9.627	Intercept	0.004	0.031	50.055	0.125	0.901	-0.059	0.067
				Time	0.002	0.004	73.339	0.512	0.611	-0.005	0.009
Bushtit	*Time	Time 2	11.815	Intercept	0.007	0.026	31.229	0.292	0.772	-0.045	0.060
				*Time	0.005	0.003	72.747	1.970	0.053	0.000	0.011
Cassin's vireo	Time	Time 2	9.639	Intercept	0.023	0.018	16.414	1.282	0.218	-0.015	0.060
				Time	0.000	0.002	73.091	-0.224	0.824	-0.003	0.003
Cedar waxwing	*Time 2		1.531	Intercept	-0.410	0.220	67.460	-1.866	0.066	-0.848	0.028
				*Time	0.216	0.060	72.129	3.577	0.001	0.096	0.336
				*Time2	-0.013	0.004	72.131	-3.383	0.001	-0.021	-0.005
		Time		Intercept	0.190	0.135	23.021	1.410	0.172	-0.089	0.468
				Time	0.016	0.013	72.976	1.221	0.226	-0.010	0.042
Dark-eyed junco	*Time	Time 2	3.145	Intercept	0.203	0.106	15.657	1.912	0.074	-0.022	0.428
				Time	0.047	0.009	73.094	5.248	0.000	0.029	0.064
Evening grosbeak	*Time	Time 2	11.562	Intercept	-0.031	0.027	68.668	-1.123	0.266	-0.085	0.024
				*Time	0.009	0.003	73.270	2.840	0.006	0.003	0.016
Northern flicker	Time	Time x SiteType	10.658	Intercept	0.021	0.018	23.656	1.191	0.246	-0.015	0.057
				Time	0.003	0.002	73.067	1.864	0.066	0.000	0.007
Olive-sided flycatcher	Time	Time 2	13.534	Intercept	0.004	0.006	79.026	0.666	0.507	-0.008	0.015
				Time	0.000	0.001	79.026	0.401	0.689	-0.001	0.002
Orange-crowned warbler	Time	*Time 2	5.588	Intercept	0.008	0.015	14.243	0.548	0.592	-0.025	0.042
				Time	0.002	0.001	72.990	1.403	0.165	-0.001	0.004
Pine siskin	*Time 2		1.817	Intercept	-0.358	0.244	77.846	-1.468	0.146	-0.844	0.128
				*Time	0.241	0.072	72.323	3.357	0.001	0.098	0.384
				*Time2	-0.016	0.005	72.333	-3.366	0.001	-0.025	-0.006
		Time		Intercept	0.351	0.131	57.219	2.683	0.010	0.089	0.612
				Time	0.004	0.015	72.778	0.278	0.782	-0.026	0.035

Species	Best Model * = signifcant @ α = 0.05, excluding	Next Best Model	Δ AICc	Parameter (β) * = signifcant @ α = 0.05	Estimate	Std. Error	df	t	*p* -value	95% Confidence Interval	
										Lower Bound	Upper Bound
Savannah sparrow	*Time	*Time x SiteType	3.000	Intercept	-0.025	0.019	28.441	-1.321	0.197	-0.064	0.014
				*Time	0.005	0.002	73.173	2.825	0.006	0.002	0.009
Song sparrow	*Time 2		2.001	Intercept	0.092	0.155	33.869	0.592	0.558	-0.224	0.407
				*Time	0.123	0.037	72.036	3.302	0.001	0.049	0.197
				*Time2	-0.009	0.002	72.036	-3.617	0.001	-0.014	-0.004
		Time		Intercept	0.486	0.114	11.150	4.244	0.001	0.234	0.737
				Time	-0.009	0.008	72.974	-1.116	0.268	-0.025	0.007
Spotted towhee	Time		1.396	Intercept	0.510	0.169	9.341	3.018	0.014	0.130	0.890
				Time	0.015	0.010	73.031	1.529	0.131	-0.005	0.036
		Time 2		Intercept	0.095	0.219	23.809	0.433	0.669	-0.358	0.547
				*Time	0.154	0.048	72.066	3.210	0.002	0.058	0.250
				*Time2	-0.009	0.003	72.066	-2.947	0.004	-0.015	-0.003
Vaux's swift	Time	Time 2	10.556	Intercept	0.023	0.018	79.000	1.319	0.191	-0.012	0.059
				Time	0.000	0.002	79.000	-0.047	0.962	-0.004	0.004
Violet-green swallow	*Time 2		1.956	*Intercept	-1.094	0.385	61.951	-2.842	0.006	-1.863	-0.325
				*Time	0.583	0.104	72.191	5.621	0.000	0.376	0.790
				*Time2	-0.033	0.007	72.192	-4.887	0.000	-0.047	-0.020
		*Time 2 x Sitetype		*Intercept	-1.234	0.522	73.133	-2.365	0.021	-2.273	-0.194
				*Time	0.705	0.151	70.150	4.660	0.000	0.404	1.007
				[site_type=CD]	0.298	0.711	73.488	0.418	0.677	-1.120	1.715
				[site_type=CD] * Time	-0.225	0.205	70.411	-1.095	0.277	-0.634	0.185
				*Time2	-0.038	0.010	70.150	-3.891	0.000	-0.058	-0.019
				[site_type=CD] * Time2	0.010	0.013	70.404	0.736	0.464	-0.017	0.037
Warbling vireo	*Time	Time x SiteType	11.761	Intercept	-0.001	0.015	14.282	-0.067	0.948	-0.032	0.030
				*Time	0.003	0.001	72.986	2.211	0.030	0.000	0.005
White-crowned sparrow	*Time x SiteType	Time	4.005	Intercept	0.093	0.116	7.954	0.801	0.447	-0.175	0.361
				*Time	0.034	0.007	71.951	4.800	0.000	0.020	0.049
				[site_type=CD]	0.044	0.154	8.151	0.286	0.782	-0.311	0.399
				*[site_type=CD] * Time	-0.034	0.010	71.965	-3.479	0.001	-0.053	-0.015
Western wood pewee	Time	Time 2	14.326	Intercept	0.001	0.005	58.899	0.212	0.833	-0.009	0.011
				Time	0.001	0.001	72.824	1.059	0.293	-0.001	0.002
Willow flycatcher	Time	*Time 2	6.052	Intercept	0.078	0.048	8.169	1.617	0.144	-0.033	0.188
				Time	0.000	0.002	72.996	-0.096	0.924	-0.005	0.005
Yellow-rumped warbler	Time	Time x SiteType	9.291	Intercept	-0.008	0.038	79.000	-0.210	0.834	-0.084	0.068
				Time	0.007	0.005	79.000	1.520	0.132	-0.002	0.016

3.9.2.3 Exploiter Guild Member Species

Linear mixed effects regression analyses for individual avian Exploiter species (as determined by AICc ranking (Burnham & Anderson 1998) four candidate models: linear time, quadratic time, linear time by development site type (Conservation Development or Planned Community Development) and quadratic time by development site type for study in Puget Sound Lowlands, 1999-2010.

Species	Best Model	Next Best Model	Δ AICc	Parameter (β) * = signifcant @ α = 0.05	Estimate	Std. Error	df	t	*p* -value	95% Confidence Interval	
										Lower Bound	Upper Bound
American crow	Time (only)	Time x SiteType	4.755	Intercept	0.175	0.125	16.316	1.405	0.179	-0.089	0.439
				*Time	0.047	0.011	73.079	4.406	0.000	0.026	0.068
Anna's hummingbird	Time (only)	Time2	9.595	Intercept	0.014	0.010	30.788	1.386	0.176	-0.007	0.036
				Time	0.000	0.001	72.765	0.401	0.690	-0.002	0.003
Barn swallow	Time (only)	Time2	10.670	Intercept	0.071	0.038	15.076	1.872	0.081	-0.010	0.153
				Time	-0.001	0.003	73.091	-0.460	0.647	-0.008	0.005
Brown-headed cowbird	Time		1.660	*Intercept	0.131	0.056	25.939	2.349	0.027	0.016	0.247
				Time	0.006	0.006	72.917	1.093	0.278	-0.005	0.017
				Intercept	-0.109	0.094	72.579	-1.160	0.250	-0.296	0.078
		Time 2		*Time	0.086	0.026	72.113	3.281	0.002	0.034	0.139
				*Time2	-0.005	0.002	72.116	-3.113	0.003	-0.009	-0.002
European starling	Time x SiteType		0.652	*Intercept	-1.023	0.350	67.062	-2.922	0.005	-1.721	-0.324
				*Time	0.498	0.099	70.107	5.040	0.000	0.301	0.695
				* [site_type=CD]	1.140	0.477	68.226	2.393	0.019	0.189	2.092
				* [site_type=CD] x Time	-0.493	0.134	70.287	-3.678	0.000	-0.761	-0.226
				* Time2	-0.027	0.006	70.107	-4.180	0.000	-0.040	-0.014
				* [site_type=CD] x Time2	0.026	0.009	70.282	3.006	0.004	0.009	0.044
		Time2 x SiteType		*Intercept	-1.023	0.350	67.062	-2.922	0.005	-1.721	-0.324
				*Time	0.498	0.099	70.107	5.040	0.000	0.301	0.695
				*[site_type=CD]	1.140	0.477	68.226	2.393	0.019	0.189	2.092
				*[site_type=CD] x Time	-0.493	0.134	70.287	-3.678	0.000	-0.761	-0.226
				*Time2	-0.027	0.006	70.107	-4.180	0.000	-0.040	-0.014
				*[site_type=CD] x Time2	0.026	0.009	70.282	3.006	0.004	0.009	0.044
House finch	Time	Time x SiteType	7.326	Intercept	0.081	0.065	23.391	1.247	0.225	-0.053	0.214
				Time	0.010	0.006	72.878	1.620	0.110	-0.002	0.023
House sparrow	Time	Time x SiteType	3.482	Intercept	0.007	0.060	16.472	0.114	0.911	-0.120	0.134
				Time	0.008	0.005	73.083	1.653	0.103	-0.002	0.019
Rock pigeon	Time	Time x SiteType	2.396	Intercept	-0.005	0.160	14.802	-0.030	0.977	-0.346	0.337
				*Time	0.037	0.013	73.090	2.807	0.006	0.011	0.063
Rufous hummingbird	Time	Time 2	7.698	Intercept	0.102	0.044	8.391	2.315	0.048	0.001	0.202
				Time	-0.001	0.002	72.978	-0.388	0.699	-0.006	0.004

Chapter 4. COMMUNICATING SCIENCE TO THE PUBLIC: A SCI-ART EXHIBITION PROPOSAL

4.1 ABSTRACT

From over-exploitation of natural resources to Global Climate Change, human societies face mounting challenges towards progress in environmental sustainability and biodiversity conservation. While scientists are actively working to address these problems through research, poor scientific literacy and policy engagement among the public suggests incomplete communication of findings, at least in part, is to blame. Communication theory illustrates the flow of information transmission and distortion, providing alternative messaging channels for increasing public awareness, understanding, and prioritization of scientific research. I propose an interactive multi-media exhibition design, entitled the *Living Science Journal*, to regularly showcase efforts in the natural sciences for informal public education. Drawing inspiration from the scientific method, research article structure, and natural history museum-style habitat dioramas, I present a relatively low resource intense format to engage scientists, artists, and the public in elevating science literacy in this age of information overload.

4.2 KEYWORDS

communication theory, science communication, natural science, exhibition, Sci-Art, multi-media, interactive, informal science education, public, citizen science, science literacy

4.3 BACKGROUND

The *science of communication* and the *communication of science* share a legacy of focus on information transmission. The modern science of communication has generated numerous theories to identify, describe, and elucidate the practice of human sharing of ideas from ancient times to the present (Craig 1993, 1999). The cybernetic tradition of communication theory (see Craig 1993 for review), most closely aligned with other branches of the natural sciences, has its foundation in the work of mid-20th Century information theorists such as Claude Shannon and Warren Weaver (Shannon and Weaver 1949). The *Shannon-Weaver model* of communication theory identified and distilled key components and relationships into a practical theoretical model (Figure 1).

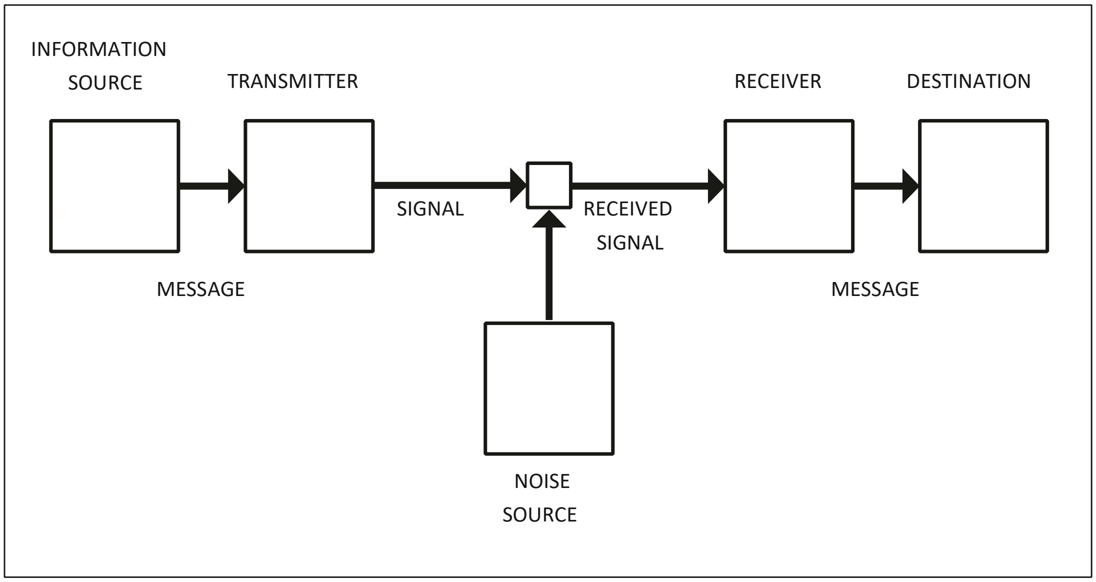

Figure 1. Schematic diagram of a general communication system (*after* Shannon & Weaver, 1949). A message passes from an information source for a transmitter to send as

> a signal, which is subject to possible source(s) of noise or distortion, before reaching a receiver, ultimately passing the message on to the destination.

Specifically, an *information source* sends a *message* via a *transmitter*; this signal is subject to varying degrees of interference, or *noise*, en route to a *receiver* that decodes the information for the *destination*. Additions include the potential for *feedback* to the *information source* from the destination (or receiver). Widely adopted across disciplines (Craig 1999) this framework led to influential contributions in the fields of quantitative ecology and biostatistics, namely diversity indices (Zar 1996) and information-theoretic model selection (Burnham and Anderson 2010). Subsequent theoretical work in human communication either extended or transcended this linear framework to include alternative philosophical and socio-political perspectives now seen by some as inherent to human information transmission.

A specialized type of communication is the exchange of scientific knowledge. A variety of existing conceptual models seek to capture this communication process between relevant constituencies in both formal and informal contexts. For instance, the dissemination of science between specialists in the conduct of science, and communication of science to policy makers (Weigold 2001). In addition, the public take in scientific knowledge for a variety of reasons, including to inform personal decision making, civic engagement, entertainment, and aesthetic appreciation (Weigold 2001, Braha 2017, Kappel and Holmen 2019). In the ecological and environmental sciences, the public engages with scientific knowledge on a wide range of issues, including sustainability (e.g., food, energy, and waste production) (Palmer et al. 2005, Voulvoulis and Burgman 2019), management of land (Taylor and Klenk 2019) and marine resources (Mangano and Sara 2017), and outdoor recreation and human health (Starnes et al. 2011).

There is ample evidence that the current state of science-public communication is in some ways inadequate. The growing mistrust of scientists and science, particularly evident in the arena of climate change (Azevedo and Marques 2017, Bjornberg et al. 2017, Cologna and Siegrist 2020), suggests that the public are not getting the full benefit of scientific knowledge. Whether these challenges are due to a lack of effective engagement by scientists (Poliakoff and Webb 2007, Besley et al. 2013, Besley 2015) a lack of adequate science literacy in the public (Fang and Wei 2010, Klucevsek 2017) or poor communication channels linking the two (Su et al. 2014, Brondi et al. 2021) is a source of debate (Landrum and Slater 2020).

My objective here is to propose a novel channel for sharing of scientific knowledge with the public. First, I present a conceptual model for how science-public communication occurs. I then identify gaps in this model and suggest some approaches that show promise for improving science-public communication. Finally, I propose an exhibit design for communicating scientific findings to the public regarding wildlife ecology in the Pacific Northwest region of the United States. The proposed communication channel is specifically focused on bridging the gap between peer reviewed scientific literature and non-professional audiences.

4.3.1 *Conceptual Model*

I propose a conceptual model for the current state of communicating science to the public (hereafter "science-public communication model," SPC model), inspired by the Shannon-Weaver model, to illustrate various channels of communication and potential means to affect positive change (Figure 2).

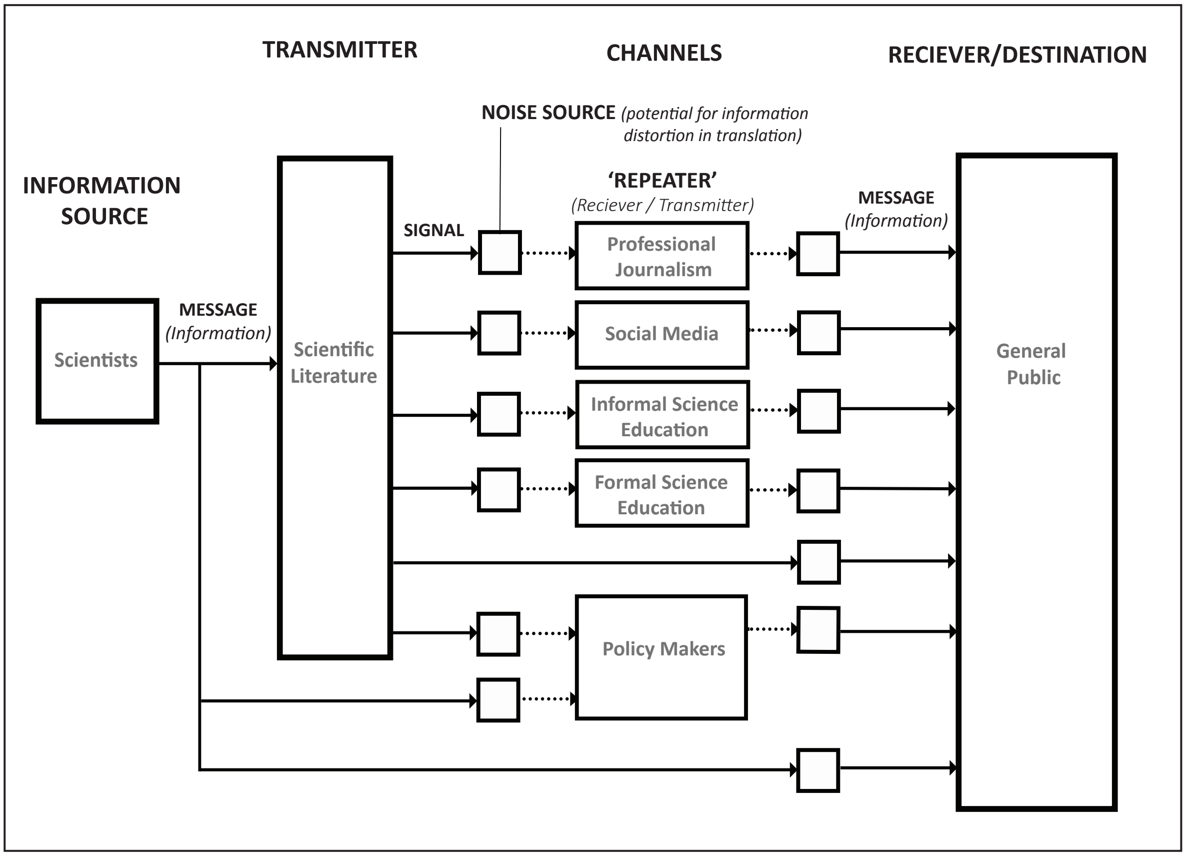

Figure 2. Proposed conceptual model describing communication of science to the public (the science-public communication model, or SPC).

4.3.1.1 Sender, Message, Transmitter

Most original science is conducted by scientists with a primary goal of informing other scientists and decision makers, with the rise of community science a key addition (Kobori et al. 2016) (Kobori et al. 2016). The SPC model seeks to explain how scientific findings make their way to the lay public. In this context, *Scientists* are the *Sender* (Information Source), as the originators of scientific knowledge, which is the ultimate *Message* to be transmitted. This collective body of knowledge is encoded through and broadcast via 1) the *Scientific Literature*, a form of *Transmitter,* and by scientists directly engaging either 2) *Policy Makers*, or 3) the *General Public.* Policy makers may in turn communicate this information to the public, though when scientists engage with the public directly, they themselves are the sole transmitter. The scientific literature includes both 'white papers', or peer-reviewed publications, and secondarily 'gray literature', or non-peer reviewed technical reports. The medium for these messages may be print or online professional and academic journals or conference and symposia proceedings. Scientists also frequently engage with policy makers directly, who may in turn communicate this knowledge to the public (Garvin 2001) . Increasingly, scientists participate in various outreach forums, sharing information directly with members of the public (Poliakoff and Webb 2007, Besley et al. 2013).

4.3.1.2 Channels

The public can ultimately receive scientific knowledge via multiple *Channels,* such as the direct engagement discussed above. More often, scientific literature acts as the information transmitter. Non-scientists may access the scientific literature directly, either through print and online subscriptions, Google Scholar, or reprints available directly from scientist's personal webpages. Use of social media by scientists is a growing phenomenon, both for extending findings to a larger audience (facebook.com, twitter.com) as well as soliciting financial support for further research (kickstarter.com, petridish.org, experiment.com), though success is mixed (Ariana Eunjung 2015, Patel 2015). The extent to which members of the lay public access this information is an interesting question in and of itself, and worthy of future investigation.

Traditionally, and dominantly, the public is exposed to scientific knowledge through one or more sub-channels, or *Repeaters*. Repeaters function as intermediate receivers of the original science *Messages*, which decode, recode, and rebroadcast to a larger audience. *Professional Journalism,* such as print, online, radio, and television outlets, regularly receive and repackage science materials. Social media, curated by non-scientists, has become a major information conduit for many in the public audience (Huber et al. 2019, Hoettecke and Allchin 2020). *Informal Science Education* takes shape through public and private museums, zoos and aquaria, online blogs, social media, libraries, and religious organizations (e.g., churches, temples, mosques) and their ancillary institutions (e.g., The Creation Museum, Petersburg, KY). *Formal Science Education* is more segregated demographically, taking the form of compulsory public, private, or home-based education of children (e.g., K-12 schooling in the United States), or higher education in the case of undergraduate (e.g., A.A., B.A., B.S. degrees) or graduate level training (e.g., M.A., M.S., Ph.D. degrees). Finally, *Policy Makers*, elected on non-elected governing officials, themselves engage with scientists directly and through the scientific literature, becoming a repeater for public framing of science knowledge, issues, and possible actions (Garvin 2001).

4.3.1.3 Receiver & Sources of Noise

The general non-science public is the ultimate *Destination* or *Receiver* for any of the channels identified above. The degree of *Noise*, or distortion, is a fundamental feature of any message. For all channels, sources of *Noise*, or the distortions of intended meaning, including modification or incompleteness, can originate in cultural processing. Culturally derived distortion, for example, can arise from different understandings of “uncertainty” in science (Landstrom et al. 2015), foundational knowledge, or trust in producers/messengers of scientific knowledge (Fischhoff 2019). Ultimately distortion of meaning may be most influenced by variable levels of public science education and scientific literacy (Holbrook and Rannikmae 2007).

4.3.2 *Identifying Gaps in Science Communication*

Two aspects of science as presented for the public work against optimal reception. First, science is perceived erroneously as a collection of 'facts.' This position misconstrues scientific investigation as a purely linear process, rather than open-ended, like viewing history merely as a collection of figures and dates to be memorized. Secondly, these 'facts' have little to no legitimacy in relation to competing domains of knowledge and are left to compete for acceptance with one another or information from other sources.

4.3.3 *Science Erroneously Perceived as a Collection of Facts*

The idea – held generally amongst professional scientists (Holbrook and Rannikmae 2007) – that science is a *process of discovery* seems to regularly suffer high to complete deterioration in translation across all channels. An indication of this failure is captured in an article paraphrasing sentiments of Marcia McNutt, past Director of the U.S. Geological Survey, and past editor-in-chief of *Science* magazine: "Scientific thinking has to be taught, and sometimes it's not taught well. Students come away thinking of science as a collection of facts, not a method. [Psychologist Andrew] Shtulman's research has shown that even many college students don't really understand what evidence is. The scientific method doesn't come naturally…" (Achenbach 2015). The degree to which science educators, in formal or informal science education forums, are themselves well versed in the scientific method figures prominently in effective communication. Professional journalists often report on scientific findings but truncate the message by omitting descriptions of the process, including study design, sample sizes, and alternative explanations for results. Additional sources of noise across all channels include difficult concepts and specialized terminology, not the least of which involve advanced computational techniques. Resulting narrative simplifications are typically intentional and predicated on authors' expectations about the scientific literacy of their audiences; however, much important information is lost that could be more effectively translated rather than omitted.

4.3.4 *Science Competes for Legitimacy with Other Forms of Knowledge*

Daniel Kahan has investigated the 'scientific communication problem' (Kahan 2010). He suggests that scientific 'facts' fight for legitimacy with individuals' personal and collective geopolitical 'world views' (Kahan et al. 2011). Furthermore, he points to research indicating that scientific literacy alone does not improve scientific understanding and acceptance but can exacerbate the polarization of viewpoints (Kahan et al. 2012). Some argue that biological processing, in the form of 'intuition' can derail both scientists and non-scientists alike in their comprehension of science-based phenomena (Shtulman 2015).

4.3.5 *Improving the Reception of Science*

While most scientists communicate primarily through the scientific literature and through formal science education (i.e., academic scientists teach courses) many scientists have heeded the call to take a larger role in science communication (Smith et al. 2013). Numerous scientists and science educators are now focusing on ways to improve the public's understanding of scientific knowledge (Levy and Ostergren 2013) and there are increasing efforts to train scientists to be better communicators (AAAS 2013, Smith et al. 2013). Additionally, educators who are not professional scientists are now armed with more effective means to communicate the scientific method (Romesburg 2014). Because there are various channels through which scientists can participate in communicating with the public, each scientist must consider how to best seek out and engage in domains that are most useful, of greatest personal interest, and best able to capitalize on a scientist's individual skills (Besley et al. 2013).

I work collaboratively with mentors and colleagues to both produce original scientific research and share these findings by publishing in peer-reviewed journals, conference symposia, and public outreach presentations. I further contribute to scientific understanding as a published natural science illustrator (Agee 2007, Marzluff et al. 2011, Marzluff 2014, Greene 2017, French et al. 2019) having earned my bachelor’s degree in visual art and history with additional coursework in scientific illustration. In my primary role as an associate professor at Cornish College, I instruct visual and performing arts undergraduates in the biological sciences and integration of science and the arts, a longstanding tradition that is recently resurgent under the “sci-art” initiative (Parks and White 2021, Stengler 2021, Trickett 2021).

I propose designing a science exhibit by integrating visual communication, i.e., use of imagery, and experiential learning, often known as “learning by doing”, to communicate scientific knowledge about wildlife ecology in the Pacific Northwest, while also providing more complete and nuanced messaging about the scientific process itself. Visual communication of science – through the use of illustrations, animations, maps, photographs, video, and other platforms – has the potential to overcome the information distortion suffered by some public audiences that receive scientific knowledge through the use of language. Images and symbols can be more accessible than the specialized vocabulary that dominates many technical papers and reports (Tufte 1983). Unfortunately, many scientists lack adequate training in visual communication (Rodriguez Estrada and Davis 2014) hampering their ability to transmit research findings across an array of audiences (Levy and Ostergren 2013). Some in contemporary science communication theory and practice advocate for user-centered design for effective visual communication (Rodriguez Estrada and Davis 2014): essentially, the explicit consideration of the user’s context in designing the content (education, values, etc.). In other words, it may be possible to increase comprehension by employing signs and symbols that are likely to be familiar to audiences irrespective of their science background, such as portraying an environment through images of common landscapes, plants, and or animals. I propose a variation on user-centered design for the proposed exhibit, which aims to present imagery infused with meaning for a wide audience, while acknowledging that not all perspectives or individual realities will be recognized (for review see Bowler et al. 2011). In this way, I anticipate that through an exhibit using multiple content streams, providing redundancy in content presented in varied display formats, along with survey evaluation and an iterative design practice, a wider audience can be more successfully engaged.

4.3.6 *Experiential Learning in Informal Science Settings*

Experiential learning (McPherson-Geyser et al. 2020) in informal science education settings has the potential to engage relatively large audiences to improve science literacy. While experiential learning empowers visitors to individually select from display offerings (e.g., interactive exhibits), the non-linear design poses significant challenges to demonstrating the spatiotemporal process of science investigation. However, many museums, zoos, and aquaria present scientific content in a self-guided free-choice learning format (Schwan et al. 2014). In contrast, use of digital screens, along with artifacts (plant and animal specimens, research instruments) and volunteer guides can reduce the need for extensive text-based learning, and present experiential ‘investigation’ that emphasizes patterns and process over authoritarian ‘facts.’

4.4 SCIENCE EXHIBIT PROPOSAL: THE LIVING SCIENCE JOURNAL (LSJ)

4.4.1 *Introduction and Rationale*

Here I propose “The Living Science Journal” (LSJ), an immersive exhibition display (Mortensen 2011) to be constructed at the Woodland Park Zoo (or similar: e.g., University of Washington’s Burke Museum of Natural History and Culture, or Cornish College of the Arts) to communicate both the process of science inquiry as well as the findings of contemporary wildlife ecology research in the Pacific Northwest. While past goal-based science exhibits overcome the dilemma of ‘science as a collection of facts,’ science as a process is still truncated to the application of concepts, as opposed to a more complete journey of inquiry (Lemagie 2011). Consequently, a key aspect unique to the proposed display is use of sequential galleries that map, both literally and figuratively, to fundamental elements of the scientific method broadly, and a peer-reviewed research article specifically. My objective is to produce a blueprint for translating science research articles, in this case wildlife ecology, into exhibitions that motivate and educate the public on issues, insights, and challenges in the field. I take inspiration from the habitat diorama, a staple of natural history museums for nearly a century, while updating the presentation format to include viewers in the process of scientific discovery (Reynolds 1988, Quinn 2006, Barclay 2015)

4.4.2 *Objectives*

I have three primary objectives for the proposed exhibit design. First, I wish to promote public science literacy across multiple ages of visitors, and second, I wish to feature wildlife science research relevant to the Pacific Northwest region. My aim is to develop a prototype exhibition design for a permanent ‘living science periodical’ center, where current research articles are ‘translated’ into interactive public exhibits on a revolving basis.

4.4.3 *Exhibit Floor Plan*

The floor plan (Figure 3) consists of a circuit of seven galleries organized to mirror the scientific process: (1) *Introduction/Study Question* (2) *Study Design,* 3) *Travel to the Field / Methods*, (4) *Observation/Data Collection,* 5) *Data Entry & Analysis,* 6) *Study Findings,* and 7) *Next Steps*. Visitors would be invited to experience the exhibit as an expedition or journey to gain science-based knowledge. Visitors will make selections at key points along the circuit, with lights and sounds that are choreographed to move them efficiently through the exhibit from start to finish.

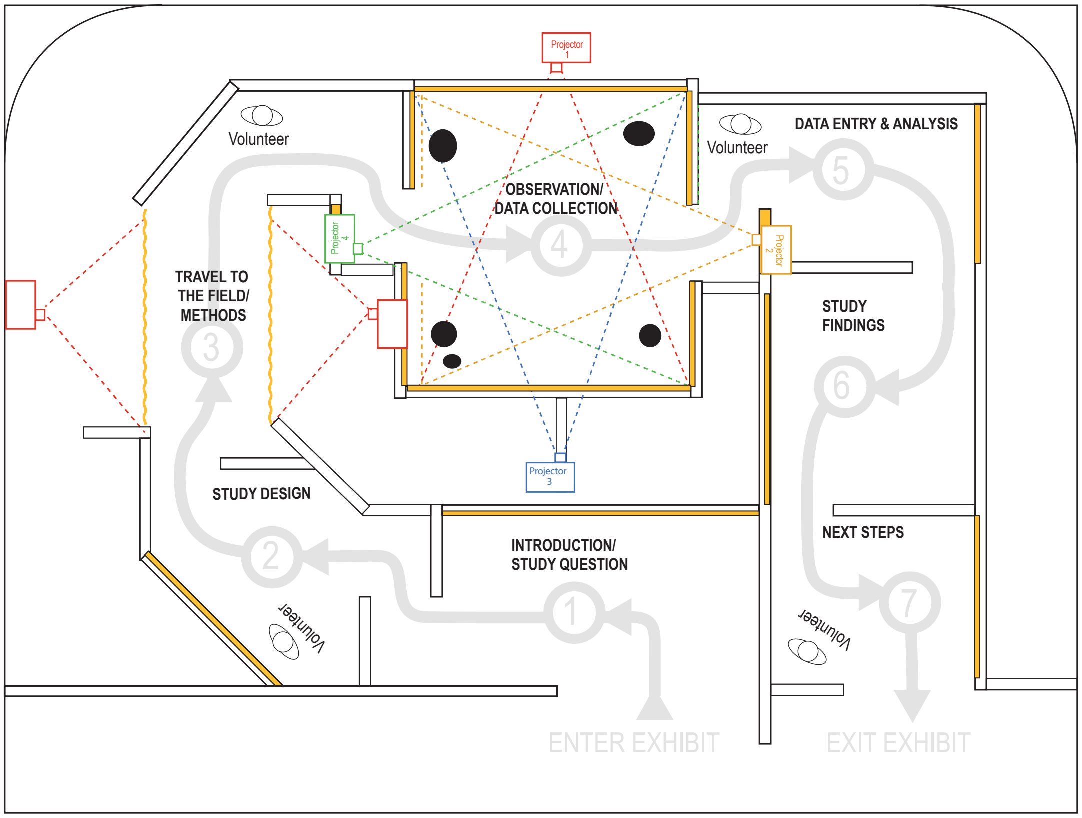

Figure 3. Floor plan of proposed immersive exhibit to showcase scientific methods in wildlife science research, detailing seven galleries through which visitors move in a circuit from start to finish. Each individual gallery represents a specific element of the scientific method or a scientific journal article. Within each gallery, visitors are invited to

make selections that alter content or outcomes displayed in later stages of the circuit, emphasizing the key aspects of science as a process of learning and discovery.

4.4.4 *Gallery Presentation Style*

I draw primary inspiration from the habitat dioramas made famous by the American Museum of Natural History in New York City, and the Field Museum of Chicago, among others (Reynolds 1988, Quinn 2006). However, I reframe the habitat diorama's static representation of natural history and repurpose the familiar space for a more interactive, dynamic journey using digital images, text, and sound. Walls will harbor recessed digital screens and, in some instances, have imagery projected from floor to ceiling. I propose the use of physical objects in the foreground of some screens or projections to further the three-dimensional look and feel that is characteristic of dioramas. Key galleries will have large format buttons or levers to make content selections. Additional interactive aspects will include select physical objects or artifacts configured with motion detection components that signal changes in projected video sequences hosted on exhibit computers. Lighted floor paths will illuminate and this, along with auditory cues, will usher visitors from one gallery to the next. Natural sounds will enhance the exhibit, such as wildlife and habitat audio tracks/field recordings for the immersive 'Data Collection' gallery.

4.4.5 *Content Messaging*

To engage multiple ages and levels of education, I propose featuring two tiers of information throughout the exhibit. All content questions will be posed in the form of testable "WHO, WHAT, WHICH, WHEN, WHERE & HOW" inquiries. The first tier will focus on a single primary study 'question' to be asked, addressed, and answered during the exhibit. This content will be prominently featured on the main wall of each gallery in simple terms using bold graphics, large text, pictures, and is symbols. In addition, several ancillary study questions (2-3) will be featured on sidewalls. This second-tier content will require more text, smaller font, and use of more sophisticated presentation forms such as slightly more complex graphs, charts, and or figures.

4.4.6 *Content*

I will briefly describe three separate research studies that could provide content for the proposed exhibit. The first study draws insights directly from my dissertation work, the second study is published research by present and former UW colleagues, and the last example would use the exhibit to conduct original research via small-scale community science.

4.4.6.1 Study I: Birds and Deforestation

The first example is based on changes to bird communities as the result of deforestation and residential housing construction in the lowlands of Central Puget Sound, Washington. The primary study question is: "WHICH habitats harbor the greatest avian species richness?" of three habitats that were studied: intact forest, newly cut forest with ongoing construction, or existing suburbs. Here I will use digital video taken from study sites in King and Snohomish Counties, including videos of both the habitats and the common avian species used in community structure analysis. Birds will be illustrated by either still photography or video. For video, individual species will be captured (mist-netting) and held briefly (< 30 minutes) to be filmed using standard digital video while housed in a Chroma-key (e.g., 'green-screen') enclosure. Video taken against the Chroma-key background will then be imported into the digital background or habitat video using various simple effects, such as fades to demonstrate the individual species presence or absence. Visitors will conduct a modified bird count (point-count) in the "Data Collection" Gallery, where either taped or live video/audio (e.g., webcam at study sites) will aid in identification of species they can record on a simple data sheet. Second tier content will follow up with additional study questions, such as "WHICH species of birds are unique to each habitat type?" and "WHICH species are lost (i.e., become locally extinct) in the most developed landscape?"

4.4.6.2 Study II: Habitat Change and Interspecific Competition

The second research project (Farwell and Marzluff 2013) focused on two common Pacific Northwest birds, the Pacific Wren (*Troglodytes pacificus*), a mature forest dwelling species, and the Bewick's Wren (*Thryomanes bewickii),* an edge-adapted species. While these two species would typically not encounter one another, human settlement has brought them together as forest fragments persist amidst housing and other development. The result can be territorial disputes for habitat and resources, with the more aggressive Bewick's Wren typically the winner. The primary study question posed is "WHO wins this battle?" Instead of conducting bird counts in the "Data Collection Gallery," viewers would predict and record the outcome of video-taped experimental disputes between a wild bird and a robotic "intruder" of the opposite species. Second tier questions include "WHERE does each species persist?" and "HOW long until the defender arrives to combat an intruder?"

4.4.6.3 Study III: Feeder Watch Community Science Project

The third potential study owes direct credit to Dr. Fred Koontz (retired Vice President of Field Conservation, Woodland Park Zoo) who, in our discussions, posed the possibility of the exhibit acting as a study, or even a simulated field-training module for community-science participation. I would realize this through a study of backyard bird feeders in the greater Seattle area. The primary study question would be "WHICH neighborhood has the most types of birds visiting feeders?" Visitors would collect data on birds arriving at feeders monitored by webcams located throughout the city (either live, or tape-delayed from earlier in the day/week). Second Tier questions would include "WHAT is the rarest bird at feeders so far?"

All studies would use the "Next Steps" gallery to provide fact sheets on the phenomena and species in question, as well as ways to learn more (e.g., literature citations, internet links, local conservation organizations and resources for potential volunteer involvement).

4.4.7 *Evaluation Survey*

I propose an outcome-based social survey as the evaluation instrument to assess visitor attitudes, learning, and overall experience of the exhibit (Moon and Blackman 2014). Survey information will be collected via a touch-screen computer interface located in the "Next Steps" gallery via an online open-source survey tool, Lime Survey (limesurvey.org), found to work well in a recent science exhibit evaluation (Lemagie 2011). Specifically, the survey will focus on five areas: 1) basic demographic data, 2) learning and retention of specific exhibit content and general environmental science literacy, 3) attitudes about and experiences of the exhibit design, and 4) support for research in the environmental sciences. Individual surveys will draw from subsets of questions (Figure 4) in each category to limit participant fatigue, with responses in the form of numerical, multiple choice (text and images), true/false, LIKERT scale, and radio button answers. Participants' ages (initial demographic data) will trigger age-appropriate questions and use of text versus symbols, along with simultaneous multiple response windows to encourage those with children to complete individual surveys. Data will be used to score the exhibit performance overall as well as performance in individual categories, testing for 1) minimum success as defined by response scores greater than 50% (e.g., Likert (1-5) 50% = 2.5), and 2) differences among groups (age, gender, residency, education level, etc.) using means, medians, and modes (Boone and Boone 2012).

Fig. 4. Evaluation Survey questions by category/outcome and responses to be accessed by participants using touchscreen computer interface hosted on open-source survey software Lime Survey (www.limesurvey.org).

Outcome	Question		Response(s)
Demographic	1.	age	numerical
	2.	gender	M, F, other
	3.	residence	Zip code
	4.	highest educational degree earned	High School, Associates, Bachelor's, Master's, Other Professional, Medical Degree, Doctorate
	5.	use of science in workplace: frequency	never, daily, weekly, monthly, annually
	6.	interest in science (least to most)	1 2 3 4 5
Specific Content		(Examples drawn from *Study #1* content)	
Introduction	1.	science typically starts with question(s)	T / F
Research design *Data Collection*	2.	researchers counted birds in more than one place because replication is a key principle in science experimentation	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	3.	birds species are named with	(a) an official common name, (b) a two-part (Latinized) scientific name, c both a & b a
Results	4.	where are the greatest number of bird species located?	(a) forests (b) new suburbs (c) existing suburbs
Next Steps /	5.	select a bird species that was found only in the forest, new suburbs, existing suburbs	select images of birds

Opportunities	6.	I plan to follow up with at least one of the outside resources made available in the "next steps" gallery	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	7.	I was previously aware of the resources made available in the "next steps" gallery	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
Wildlife Ecology	1.	wildlife ecology is a collection of facts about the natural world	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	2.	wildlife ecology is a process of questioning, experimentation, and discovery	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	3.	peer-reviewed journal articles are the gold-standard for scientific information	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
Support / Acceptance	1.	wildlife ecology is an activity only practiced by professional scientists	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	2.	wildlife ecology provides critical understanding for conservation of natural resources	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	3.	wildlife ecology can be interesting way to learn about the natural world and humans place in it	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	4.1	wildlife ecology research activities are worth supporting	Y / N
	4.2	if "yes” to 4.1:	

	a	time / volunteer	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	b	private donations	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	c	government funding	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	5.	I plan to follow up with at least one of the outside resources made available in the "next steps" gallery	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	1.	I spent _____________ minutes in the exhibit:	5 10 15 20 25 30 >30
	2.	I enjoyed experiencing this exhibit	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	3.	It was fun to see the process of solving the initial question	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	4.	the 'advance to the next room/gallery' cues (visual & auditory) were easy to follow	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	5.		

Exhibit Format		the 'circuit-nature' of the exhibit made me feel rushed	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	6	touch screen interface was easy to use	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	7.	projected imagery was engaging	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	8.	the themed galleries/rooms were too constraining	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	9.	the volunteer 'guides' were helpful	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	10.	the text was too much to read	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	11.	my experience of the exhibit at LSJ was positive	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	12.	I learned new information from the exhibit	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree
	13.	I plan on returning to LSJ should new exhibits open in the future	5- strongly agree, 4 – agree, 3 – undecided neutral, 2 – disagree, 1- strongly disagree

4.4.8 *Demographic Data*

Participants will be asked for age, area of residence, education level, use of science in their workplace (if an adult) or interest in science in school (if a child); no identifiable information such as name, birthdate, social security number, phone number, or address (except for zip code) will be collected to ensure participant privacy. Should the pilot exhibit be successful enough to offer future exhibitions, participants will be issued bar-coded plastic cards/tags like 'club cards' commonly used by supermarket and retail chains to track purchases and encourage repeat visitation. These tags will still maintain visitor survey anonymity yet allow LSJ monitors to follow repeat visitors and thereby detect longer-term changes in learning outcomes and funding support. Repeat visitation and survey participation will be encouraged by entering codes in random draws/raffles for future LSJ exhibition tickets or memberships, guest visits to local area research projects, topical publications, and tickets to researcher speaking events.

4.4.9 *Learning and Retention of Exhibit Content & Science Literacy*

A key objective of the LSJ exhibit format is to educate visitors based on current environmental science research findings. Success will be assessed by querying visitors on specific information displayed. Questions will make use of visual images and symbols (Tufte 1983) whenever possible to enhance recall and elevate the survey experience. Questions will be filtered by age of survey participants to reflect age-appropriate expectations for learning the display content.

A second key objective is to promote increased science literacy in general, and literacy regarding wildlife ecology specifically. This objective is the driving force behind the exhibit format as a series of thematically linked galleries, reinforcing science as a process of experimentation and peer-review of results. Participants will be asked about general principles related to environmental science practiced as a recursive process, that is searching for patterns and mechanisms to understand phenomena and provide information to governmental and non-governmental entities for environmental stewardship.

4.4.10 *Experience of Exhibit Design and Format*

Extended life for the LSJ will be dependent on the exhibit's ability to immerse and inspire visitors in uniquely translated experiences. Participants' attitudes about the exhibit space, use of imagery, text, symbols, visual cues, and auditory cues are all of importance in shaping the overall experience and should be evaluated to identify weaknesses and guide continued experimentation and improvements.

4.4.11 *Support for Wildlife Ecology Research*

Environmental research is increasingly difficult as academic competition for federal grants becomes fiercer (Howard and Laird 2013). Collaboration across academic, non-profit, and for-profit entities to further scientific research is critical, as is public support for science funding. However, the likelihood of public donations and private philanthropy depends on an appreciation for science as a means of understanding and as a relevant partner in helping guide the future. To this end, science-based exhibits must find the means to deliver research findings most effectively to a larger audience, as well as garner their financial support for continued enterprise. Select survey questions will be aimed at registering visitor support for wildlife ecology research.

4.5 CONCLUSION

Public awareness of science-based issues, current research findings, and means to deploy scientific understanding to solve societal issues is critically important but complex. Models of how information is communicated generally (Shannon and Weaver 1949), and how science is communicated specifically (Klucevsek 2017), detail a range of modalities from direct engagement with scientists, to published findings, which are then interpreted and re-broadcast to audiences through journalism, social media, formal and informal education, and policy makers. However, the potential for degraded communication or misunderstanding is influenced by the introduction of noise, or signal loss/distortion. Noise, not unlike a school-yard game of 'telephone,' likely increases with transmission distance, i.e., translation of knowledge by multiple parties, and science literacy of the receiver.

I propose a novel science-art integration using an exhibition model to reduce transmission length and increase receiver sensitivity. Museum-style exhibitions would feature ecological science research by combining rich visual imagery and experiential learning techniques to engage public audiences. Content would draw from either recently published peer-reviewed science findings or would be workshopped with researchers to produce original citizen science projects. Integral to the design are social surveys of participant learning for insights to refine and improve upon future iterations to communicate science more effectively to a broad audience. Seattle area venues for the proposed exhibit include Cornish College of the Arts (new public gallery space opening Fall 2022 at Boren and Lenora avenues), Burke Museum of Natural History and Culture at the University of Washington, The Pacific Science Center, and Woodland Park Zoo.

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Chapter 5. NATURAL SCIENCE ILLUSTRATIONS: WELCOME TO SUBIRDIA

5.1 INTRODUCTION

Human renderings of the natural world have a long and storied history. From the Pleistocene cave drawings some 35,000 years ago in Europe and Indonesia (Aubert et al. 2014), through the highly influential science illustration during the 19th century (Blum 1993) to the myriad professional science illustrators working today (e.g., Guild of Natural Science Illustrators, www.gnsi.org), representational images have been used to document the natural world. Birds have been a particularly rich subject in the pantheon of nature-related art through the ages (Wheye and Kennedy 2008), with prolific artists like John James Audubon and Louis Agassiz Fuertes (Peck 1982) producing work of such exactitude and grace as to make them household names among professional and amateur ornithologists alike (for critique of Audubon, see Lanham 2021). Equally, though far less credited, contributions came from female illustrators such as Elizabeth Gould (Wetzel 2021), whose work helped popularize the books of her ornithologist husband, John Gould. However, representations of birds can go well beyond spectacular celebration of individual species and habitat, with the ability to inform and inspire through ecological education (Hunt 2006). In this section I present 41 original illustrations I created to accompany the text of Professor John Marzluff's book *Welcome to Subirdia: Sharing Our Neighborhoods with Robins, Wrens, Woodpeckers and Other Wildlife* (Marzluff 2014).

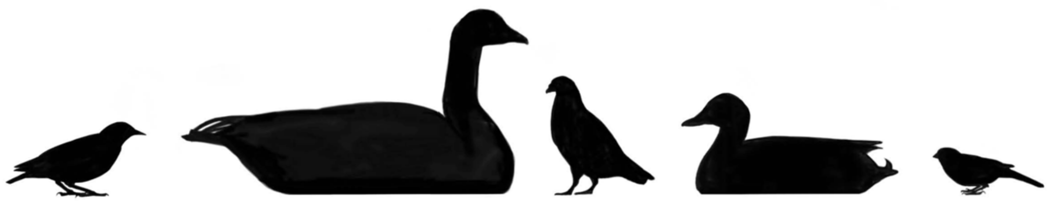
5.2 IMAGE PRODUCTION: MEDIUM AND PROCESS

The images that follow were created on a Wacom Cintiq 13HD digital screen with stylus using the software Sketchbook Pro 6 (Autodesk 2014). This digital workflow permitted me the flexibility to produce highly editable freehand drawings, an asset when working collaboratively. I created separate layers for foreground and background elements in each composition, allowing for iterative changes based on author and editor feedback as we worked to produce the most effective combinations of subject, action, and environment to communicate the scientific concepts and findings described in the text.

5.3 SELECTING ILLUSTRATION SUBJECTS

The subjects of images were collaboratively chosen by Professor Marzluff and me to illustrate key ecological concepts and findings described in *Welcome to Subirdia* (Marzluff 2014). While the order in which the illustrations appear in the book was determined by the book's narrative, I have reorganized the images here to demonstrate their thematic relationship to many aspects of my first two dissertation chapters: 1) community ecology, 2) species interactions, 3) field methods, 4) behavioral adaptations, 5) species-specific natural history, 6) human impacts: facilitation and habitat degradation, and 7) non-avian wildlife.

Exploiters I. (title page, throughout text)
The publisher (Yale University Press) requested a “Decorative Break” for use on the Title Page and to mark transitions between sections throughout the text. We selected the ‘Fab 5’, or five ‘exploiter species’ (Blair 1996), which are the avian species most representative of highly urbanized areas in North America: European Starling (*Sturnus vulgaris*), Canada Goose (*Branta canadensis*), Rock Pigeon (*Columba livia*), Mallard Duck (*Anas Platyrhynchos*), and European House Sparrow (*Passer domesticus*).



Exploiters II. (p.16)

Three of the five avian species most common to many urban areas globally, shown here in New York City's Central Park 'exploiting' food spilled by a carriage horse: Rock Pigeon *(Columba livia)*, European House Sparrow *(Passer domesticus)*, and European Starling *(Sturnus vulgaris).*

Exploiters III: Globally (p.35)
A suite of 'Exploiter' species from various parts of the Globe: Barn Owl (*Tyto alba*), House Finch (*Haemorhous mexicanus*), Barn Swallow (*Hirundo rustica*), Black Redstart (*Phoenicurus ochruros*), Hooded Crow (*Corvus cornix*), and Rose-ringed Parakeet (*Psittacula krameri)*.

Avoiders Globally (p.32)
Avian species that avoid areas of high human development around the World, including Yellow-billed Cuckoo (*Coccyzus americanus*), Hairy Woodpecker (*Picoides villosus*), Black-throated Gray Warbler (*Setophaga nigrescens),* Eurasian Wryneck (*Jynx torquilla*), Jackdaw (*Corvus monedula*), and Nightingale (*Luscinia megarhynchos).*

Adaptors Globally (p.34)
International sample of avian species adaptable to areas of moderate human development: (European) Northern Goshawk (*Accipiter gentilis*), White-crowned Sparrow (*Zonotrichia leucophrys*), Northern Cardinal (*Cardinalis cardinalis),* Black-billed Magpie (*Pica hudsonia*), European Blackbird (*Turdus merula*), and Great Tit (*Parus major*).

Waterfowl Diversity in Alaska (p.15)
Outskirts of Metropolitan areas can harbor surprising diversity, as in three species of native waterfowl near Anchorage, Alaska: Harlequin Duck (*Histrionicus histrionicus*), Mallard Duck (*Anas platyrhynchos*), and Canada Goose (*Branta Canadensis*).

5.3.2 *Species Interactions*

Competition: Wrens (p.24)
Urban development in the Pacific Northwest region has fomented competition among two previously separated species, the human-adaptable Bewick's Wren (*Thryomanes bewickii*) and the human-avoiding Pacific Wren (*Troglodytes pacificus*) (Farwell and Marzluff 2013).

Evolution I: Urban Dark-eyed Juncos (p.118)

Dark-eyed Juncos (*Junco hyemalis*) in urban areas have demonstrated rapid evolution in sexually selected tail plumage coloration, with decreases in the amount of white in an urban population, relative to mountain populations, correlating with decreased aggression and increased brood attentiveness (Yeh 2004).

Evolution II. Peppered Moths and European Jay (p.127)
The industrial revolution, and concomitant air pollution, infused some European forests with soot that darkened the exterior of many trees. As a result, dark morph Peppered Moths (*Biston betularia*) enjoyed higher survival relative to their lighter counterparts, who were gobbled up by insectivorous predators like the Eurasian Jay (*Garrulus glandarius*).

Evolution III. Noisy Miner (p.131)

Australia's Noisy Miner (*Manorina melanocephala*) is one of a number of bird species that has been shown to alter the pitch (increase frequency) of males' solicitation songs to literally rise above the background din of urban and suburban noise (Lowry et al. 2012)

Evolution III. European Sparrows (p.137)
Busts depict morphological similarities and differences among three closely related species of European sparrows: House Sparrow (*Passer domesticus*), Spanish Sparrow (*Passer hispaniolensis*), and Italian Sparrow (*Passer italiae*).

Predator-prey: Pine Siskin Captured by Sharp-shinned Hawk (p.60)
Predation is a major cause of mortality for small songbirds, including Pine Siskins (*Spinus pinus*) that are opportunistically preyed upon by Sharp-shinned hawks (*Accipiter striatus)* at bird feeders.

Predator-Prey II. American Crows Mobbing Red-tailed Hawk (p.62)
A common sight across North America, American Crows (*Corvus brachyrhynchos*) use mobbing behavior to reduce the threat of a predator in their midst, such as the Red-tailed Hawk (*Buteo jamaicensis*).

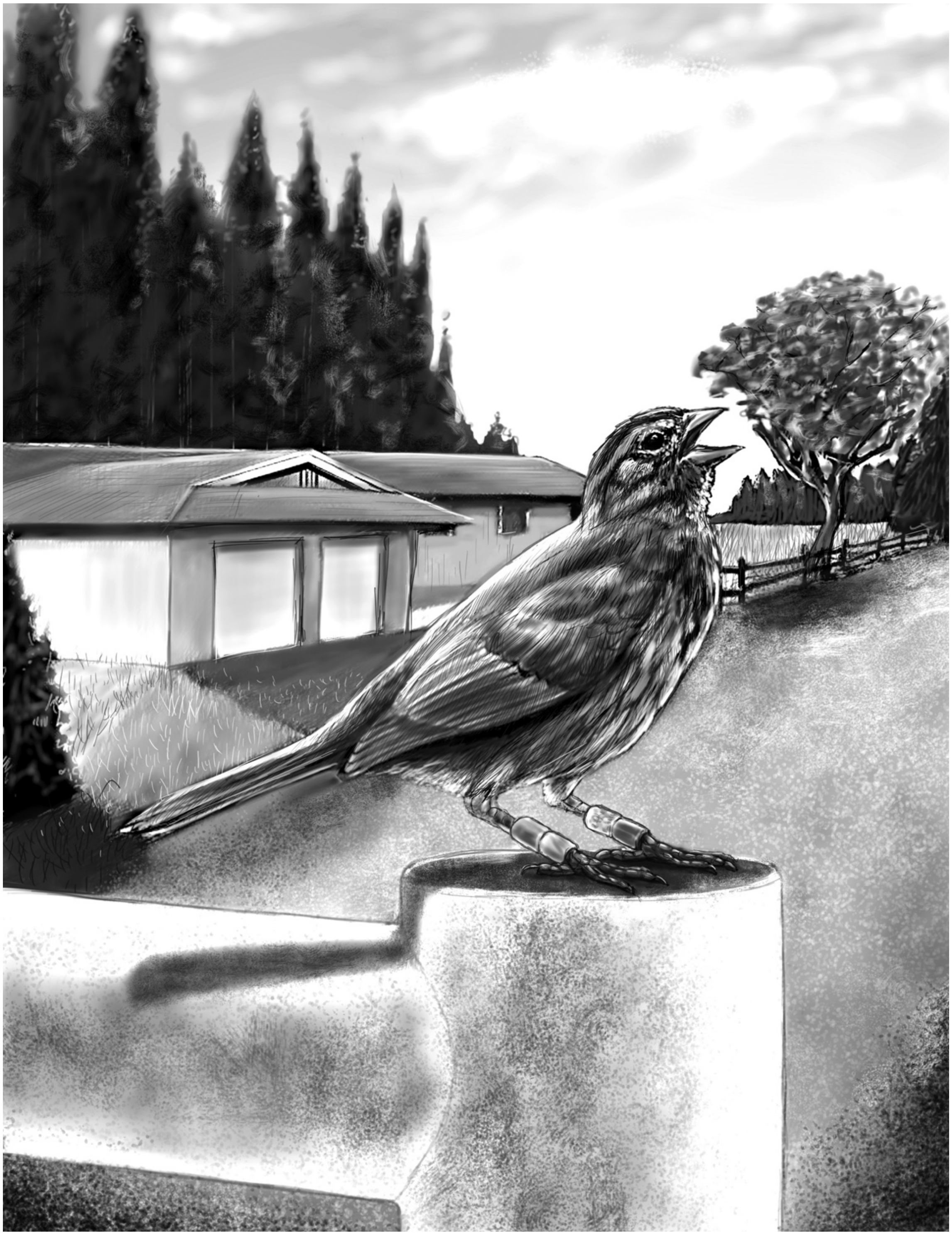
Predator-prey III. (p.84)
Recent estimates have pointed to domestic cats *(Felis catus)* as the single greatest source of mortality in birds (Loss et al. 2013), like this individual with a dead European Robin *(Erithacus rubecula)*.

5.3.3 *Field Biology*

Field Biology I: Spotted Towhee in Bander’s Grip (p.87)
Field ornithology often demands the capture and banding of study subjects; to handle passerines safely, researchers employ the Bander’s Grip, which immobilizes a bird, like the pictured Spotted Towhee (*Pipilo maculatus*), yet allows for attachment and reading of aluminum and colored plastic leg bands for future identification.

Field Biology II: Song Sparrow Singing in Suburbs (p.72)

The unique combination of colored and aluminum leg bands, as pictured in this singing male Song Sparrow (*Melospiza melodia*) allows for 're-sighting', or non-invasive serial identification of individual birds in demographic studies of bird populations.



Field Biology III: Bushtit at Nest (p.74)
Finding an active Bushtit (Psaltriparus minimus) nest allows for the monitoring of breeding success in many avian field studies.

Field Biology IV: Fledgling American Robin with Radio Transmitter (p.93)
Miniaturization of radio-telemetry transmitters has allowed numerous research studies to gather spatial movement and survival data on small-bodied passerine species like this American Robin (*Turdus americanus*) fledgling.

5.3.4 *Behavioral Adaptations*

Behavioral Adaptations I: Ex-urban Great-horned Owl (Opposite p.1)
The Great-horned Owl (*Bubo virginianus*) enjoys a wide species distribution, with individuals, like this vocalizing ex-urban dweller, occupying varied habitats.

Behavioral Adaptations II: Urban Peregrine Falcon (p.104)
Another bird of prey species, the Peregrine Falcon (*Falco peregrinus*), has not only come back from Endangered Species status in recent decades, but thrives in many urban areas.

Behavioral Adaptations III: Suburban Nesting Bewick's Wren (Book Cover)
Bewick's Wrens are highly adaptable, known to nest in and on all sorts of 'unusual' substrates among human dwellings.

Behavioral Adaptations IV: Pyramiding Inca Doves (p.70)
Inca doves (*Columbina inca*), though native to arid environments often warm by day, utilize a comical form of social huddling behavior, termed ‘pyramiding,’ to thermoregulate during cool night and early morning temperatures.

Behavioral Adaptations V: Anna’s Hummingbird at Feeder (p. 10)

Anna’s hummingbirds (*Calypte anna*) have adapted to overwintering at northerly latitudes they formerly migrated from during winter, thanks in part to human-provided nutrients at feeders.

Behavioral Adaptations VI: Black-headed Grosbeak (p.82)

Black-headed Grosbeaks (*Pheucticus melanocephalus*) are a neotropical migrant species eager to take advantage of human-provided food, such as black oil sunflower (*Helianthus annuus*) seeds.

Behavioral Adaptations VII: Brewer's Blackbirds at Costco (p.101)
Brewer's Blackbirds (*Euphagus cyanocephalus*) can regularly be seen outside 'big box' retailers like Costco, waiting to gain access to stray food in cafeteria areas.

Behavioral Adaptations VIII: Red-headed Woodpecker (p.107)
Research has demonstrated Red-headed Woodpeckers (*Melanerpes erythrocephalus*) often make tree cavities on golf courses, undeterred by human activities.

Behavioral Adaptations IX: Oystercatchers at St. Andrews (p.115)
Eurasian Oystercatchers (*Haematopus ostralegus*) are another bird species willing to forage on golf courses, like the course at St. Andrews in Scotland, United Kingdom.

5.3.5 *Natural History*

Natural History I: Rufous Hummingbird (p.39)
Illustration of a male Rufous Hummingbird (*Selasphorus rufus*) and gorget, or spectacular throat plumage, perched on a budding salmon berry (*Rubus spectabilis)* branch.

Natural History II: Red-breasted Sapsucker (p.50)

Red-breasted Sapsuckers (*Sphyrapicus ruber*) ‘farm’ sap, and the insects trapped by the oozing tree substance, by drilling matrices of small holes in tree trunks, like that of the paper birch (*Betula papyrifera*).

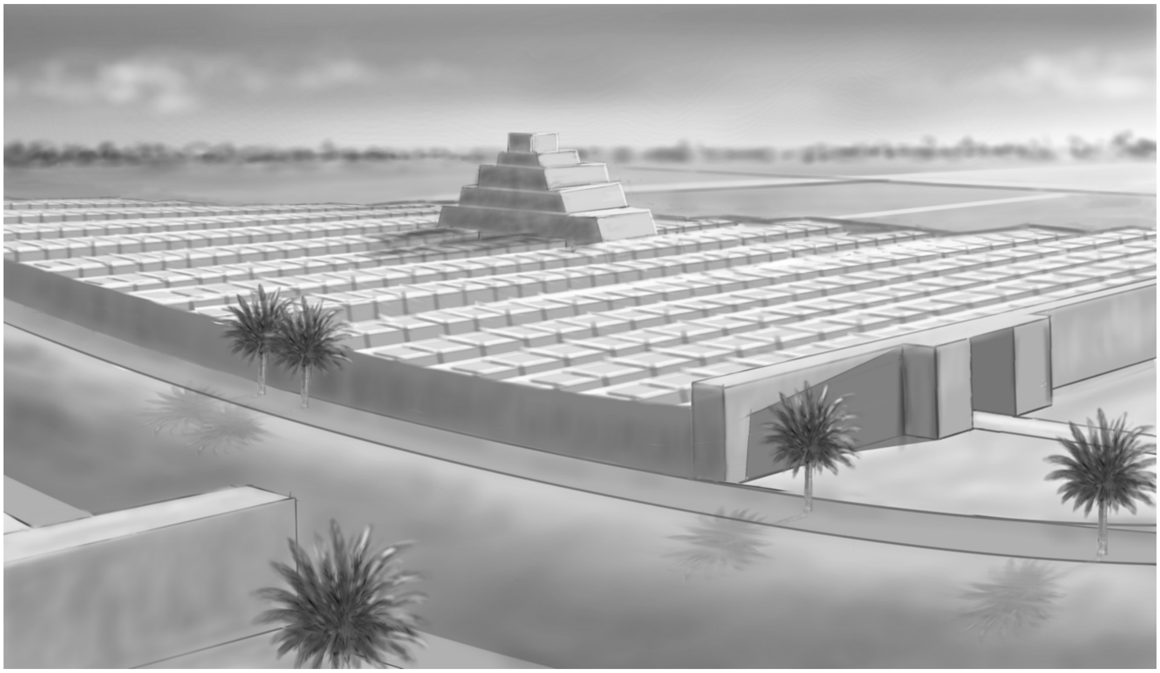
Natural History III: Swainson's Thrush Nest (p.226)
Swainson's Thrush (*Catharus ustulatus*) nests are beautifully lined with lace-like skeletonized leaves.

5.3.6 *Human Impacts*

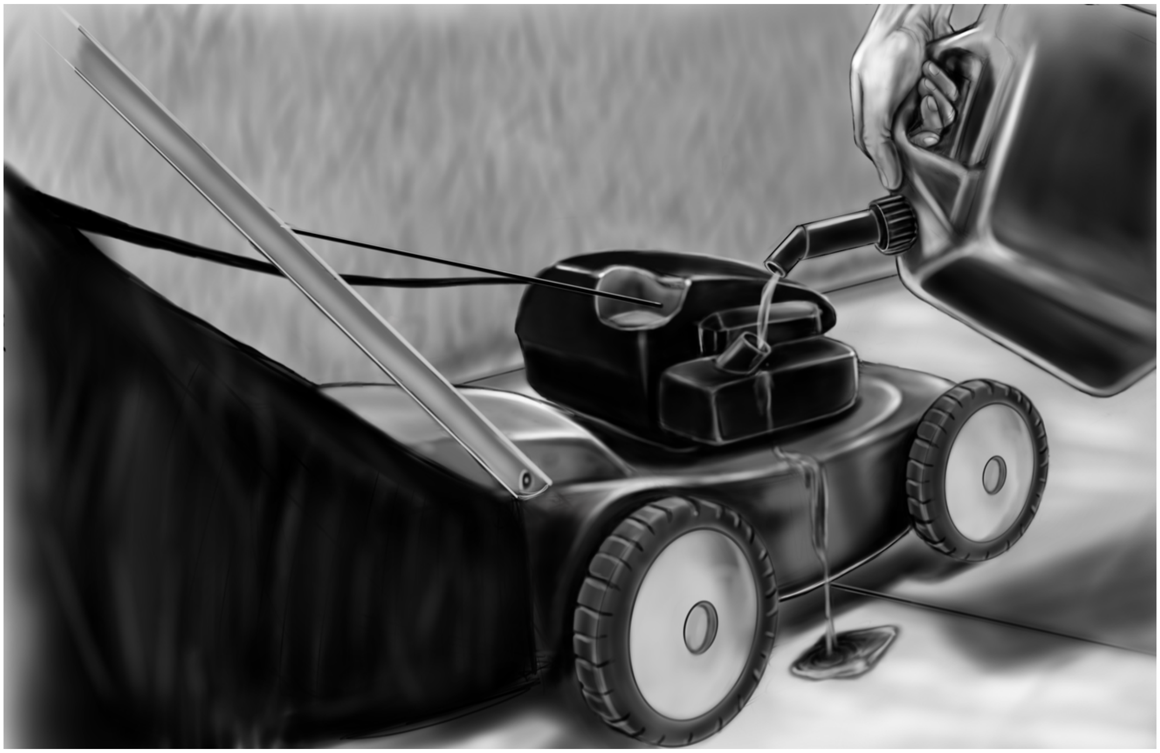
Human Impacts I: Children Feeding Wildlife in Alajuela, Costa Rica (p.214)
Biophilia (Wilson 1984) is particularly strong with children, like these youngsters feeding Rock Pigeons and Variegated Squirrels (*Sciurus variegatoides*) at one of many urban parks in the city of Alajuela, Costa Rica.

Human Impacts II: Habitat Restoration in Santa Elaina, Costa Rica (p.176)
Retired American physician Dr. Stephen Humphreys resides full time on land that was once a denuded horse ranch, adjacent to a pristine Costa Rican national park. Dr. Humphreys inspires students and visiting ecologists as he works tirelessly to replenish the vegetation and ecosystem function that was lost over decades of using the land for ranching.

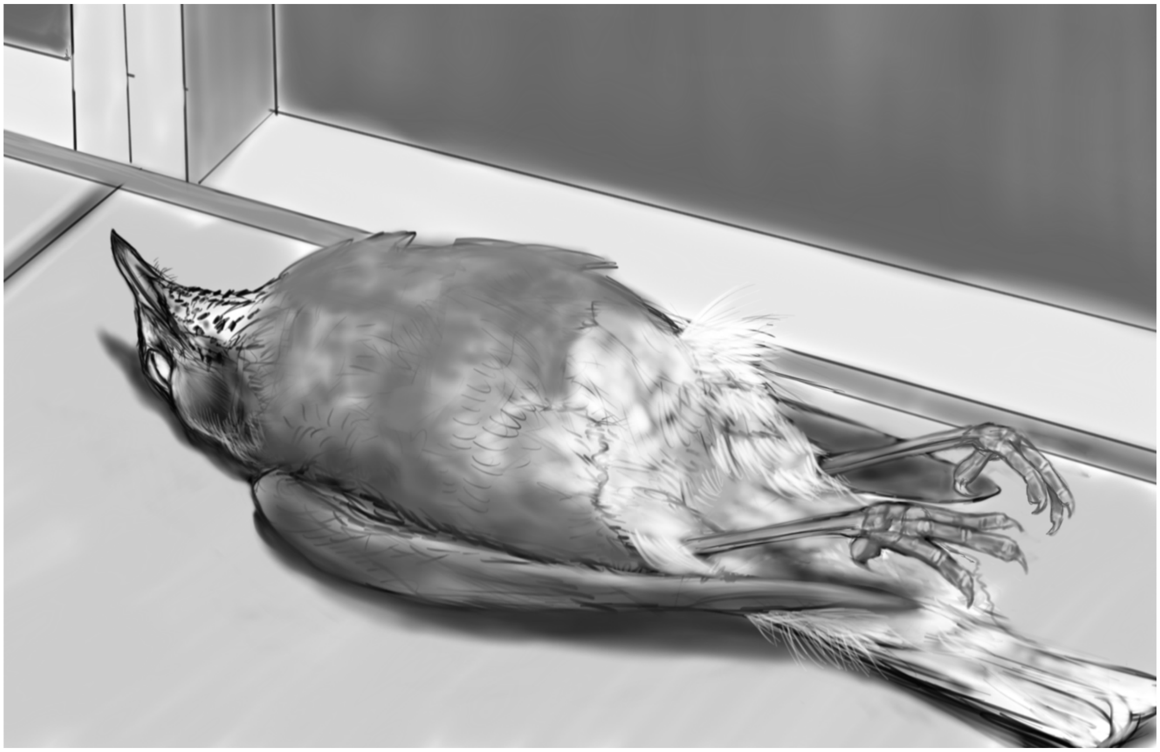
Human Impacts III: Early Mesopotamian City (p.6)
Impressionistic rendering of an early ‘urban’ landscape.



Human Impacts IV: Gasoline Spill from Lawnmower (p.183)
A common suburban activity that, summed across suburbs, amounts to a vast quantity of pollution entering the environment on an annual basis.



Human Impacts V: American Robin Window-strike (p.190)
The scene of death-by-window, an American Robin (*Turdus migratorius*) constitutes a single avian tragedy that cumulatively culls hundreds of thousands of birds from the ranks of the living.



Human Impacts VI: Vaux’s Swifts in Monroe, Washington (p.203)

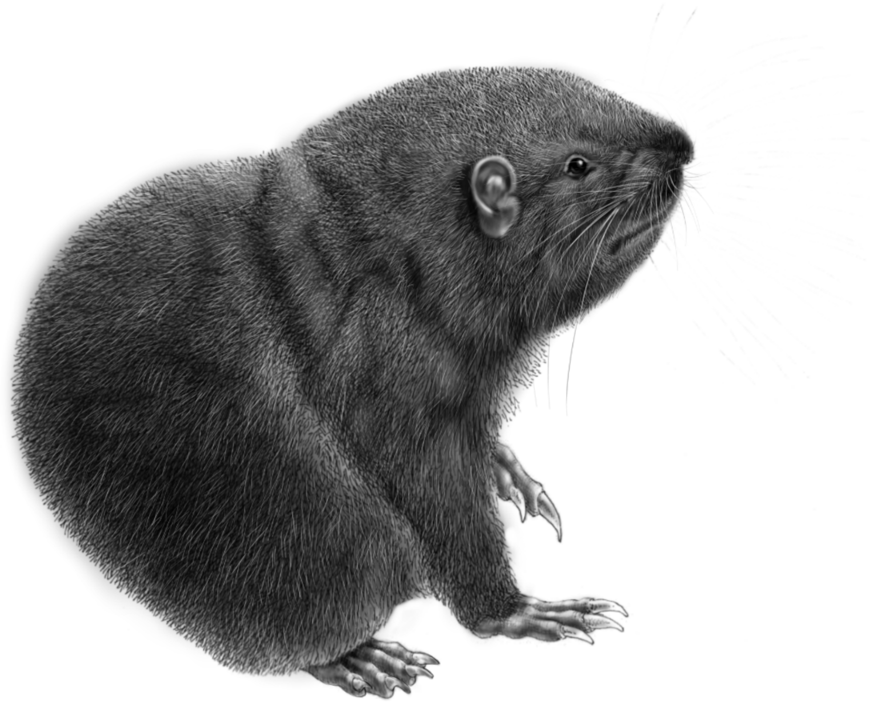
Human ‘artifactual’ facilitation, where large numbers of Vaux’s Swifts (*Chaetura vauxi*) take shelter in a man-made structure.

5.3.7 *Non-Avian Wildlife*

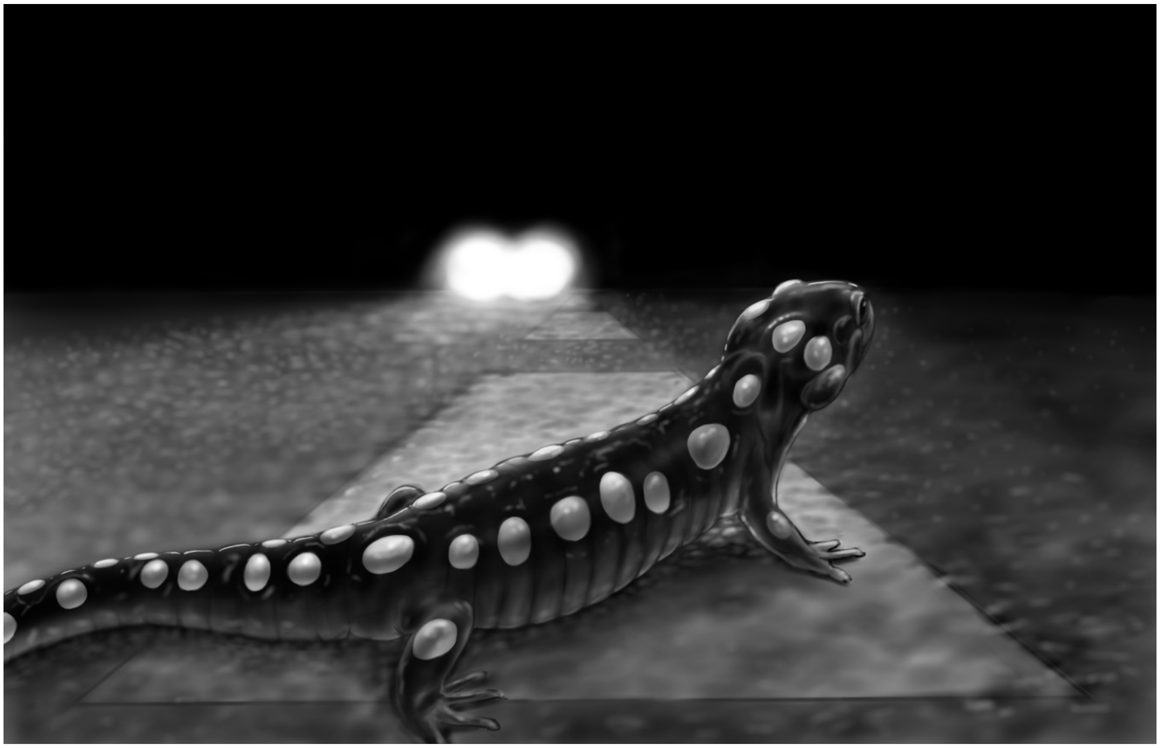
Non-avian Wildlife I: Baird's Tapir *(Tapirus bairdii),* Corcovado National Park, Costa Rica (p.210) Exemplifying an exceedingly rare species that is seemingly incompatible with large scale landscape alteration by humans.

Non-avian Wildlife I: Gray-headed Flying Foxes (*Pteropus poliocephalus)* in Melbourne, Australia (p.149). A species that readily makes use of a highly visited urban nature oasis.

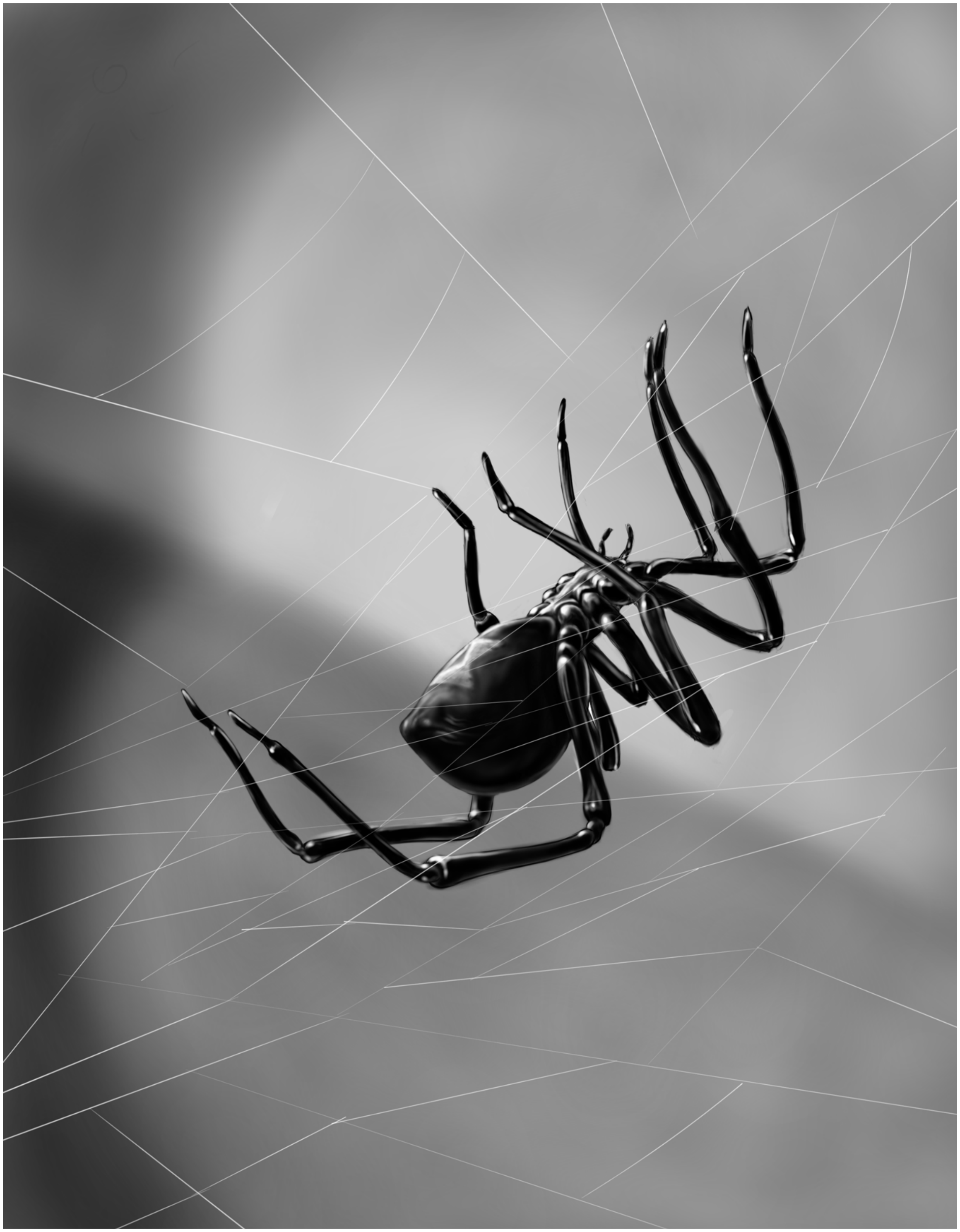
Non-avian Wildlife I: Mountain beaver (p.151)
An endemic species to Washington State, and the sole extent example of its genus, the Mountain Beaver (*Aplodontia rufa*) is a resourceful, albeit slow-moving, ground dweller.



Non-avian Wildlife I: Spotted Salamander (p.160)
Vulnerable to vehicular mortality during breeding movements, the Spotted Salamander (*Ambystoma maculatum*) benefits from communities willing to alter traffic patterns at key points in the year.



Non-avian Wildlife I: Black-widow Spider (p.166)
A highly recognizable arachnid, the Black-widow Spider (*Latrodectus sp.)* is a common urban/suburban resident.



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VITA

Jack DeLap is an ecologist, educator, and illustrator, dedicated to integrating arts and sciences. A dual citizen of the United States and Canada, Jack was raised in Southern California with extended trips to British Columbia since childhood. In 1992 he earned his B.A. in Fine Art (painting & drawing) and History at Pitzer College in Claremont, California. Following employment in the contemporary fine art field (galleries, art services), Jack followed his lifelong passion for birds by shifting to work as an ornithological field technician on various raptor and songbird research projects. He completed his M.Sc. Degree in Wildlife Biology (Colorado State University, 2001) investigating the impacts of human recreation on wildlife communities in the Yampa River Valley of northwestern Colorado. Jack shifted to urban ecology, studying the effects of residential development on forest landscapes and local breeding bird communities in the Central Lowlands of Puget Sound, completing his Ph.D. in Environmental and Forest Sciences (University of Washington, 2022). He has published scientific research on urban ecology, avian behavior, the effects of human recreation on wildlife, and landscape conservation under climate change. Jack is currently an Associate Professor in the Department of Humanities and Sciences at Cornish College of the Arts (CCA) in Seattle, WA. A past recipient of the CCA Excellence in Teaching Award (2017), Jack develops and instructs an array of courses in science (environmental science & sustainability, evolutionary biology, urban ecology) and sci-art (scientific illustration, science in wildlife documentary film, the art & science of taxidermy). A member of the Guild of Natural Science Illustrators, Jack has contributed original illustrations to professional journals and books including *Whooping Cranes: Biology and Conservation* (2019), *The Mezcal Rush: Explorations in Agave Country* (2017), *Welcome to Subirdia: Sharing Our*

Neighborhoods with Wrens, Robins, Woodpeckers and Other Wildlife (2014) and *The Steward's Fork* (2007).