Behavioral Responses of Willow Flycatchers, *Empidonax traillii*, to a Heterogeneous Environment

Amanda V. Bakian
*Utah State University*

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BEHAVIORAL RESPONSES OF WILLOW FLYCATCHERS, EMPIDONAX TRAILLI, TO A HETEROGENEOUS ENVIRONMENT

by

Amanda V. Bakian

A dissertation submitted in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Ecology

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UTAH STATE UNIVERSITY
Logan, Utah
2011
ABSTRACT

Behavioral Responses of Willow Flycatchers, *Empidonax traillii*, to a Heterogeneous Environment

by

Amanda V. Bakian, Doctor of Philosophy

Utah State University, 2011

Major Professor: Dr. Kimberly A. Sullivan
Department: Biology

Spatial heterogeneity impacts population and community-level dynamics including species-level dispersal patterns, the use and availability of refugia, predator/prey dynamics, and reproductive fitness. Understanding how wild animal populations respond to environmental heterogeneity is essential for their proper management and conservation. In this study, I examine the responses of Willow Flycatchers to spatial heterogeneity in the distribution of their food and habitat resources. Over the course of three breeding seasons, I radio-tracked Willow Flycatchers at Fish Creek in Manti-La Sal National Forest in Utah, recorded detailed behavior data at each radio location, and collected fecal, feather and insect samples. I formulated individual and population-level Bayesian spatial resource selection functions to model Willow Flycatcher foraging and vocalization behavior on multiple scales. These models indicate that vocalization and foraging behavior are spatially segregated within the home ranges of Willow Flycatchers. Further, Willow Flycatchers were found to use mature riparian habitat for vocalizing while they used a variety of habitat types for foraging. The insect samples were used to identify distinct carbon and nitrogen stable isotope signatures for the aquatic and terrestrial insect communities at
Fish Creek. In conjunction with the fecal samples, I used the stable isotope signatures to
determine the contribution of aquatic versus terrestrial insects to the Willow Flycatcher diet.
Aquatic insects comprised a larger proportion of the diet of adult than nestling Willow
Flycatchers. This suggests that adult flycatchers consume a diet that is distinct from the one they
feed to their nestlings. Finally, I compared space use characteristics in two populations of Willow
Flycatchers: a population of the endangered Southwestern Willow Flycatcher at Roosevelt Lake,
Arizona and another belonging to a non-endangered subspecies of Willow Flycatcher at Fish
Creek, Utah. Differences in space use were found largely among breeding flycatchers while space
use characteristics in non-breeding Willow Flycatchers did not differ across populations. This
suggests that space use patterns in non-breeding Southwestern Willow Flycatchers may be
generalizable to non-breeding flycatchers from non-endangered populations. This study expands
our understanding of how Willow Flycatchers respond to spatial heterogeneity while its key
findings have management and conservation implications for the species.

(137 pages)
DEDICATION

The writing of this dissertation has been the greatest challenge of my life thus far. The reason that this, and not some other event, has been my life’s greatest challenge is because of my parents, Linda and Victor Bakian. Your parenting and guidance over the years have allowed for my greatest challenge to be of my own making. Therefore I want to dedicate my dissertation to you, Mom and Dad. Over the years, you have instilled a curiosity in me and a lack of fear, and your influence created the lenses through which I view and interpret the world. Although this curiosity has currently led me to ponder ecological processes and patterns, where it will lead me in the future remains to be seen. Wherever the road takes me, I am so grateful that your guidance, wisdom, support, and love have finally led me here.
ACKNOWLEDGMENTS

This dissertation would not have been possible without the support and assistance of many people. First, I would like to thank Kim Sullivan who has been a wonderful mentor, role model, collaborator, and friend to me. Thank you to my current and previous committee members for their guidance, insight, and support including Richard Cutler, Morgan Ernest, Thomas Edwards, Ethan White, Jim Haefner, and Dan Rosenberg. I am grateful to Eben Paxton for offering me this project, providing me the opportunity to work with Willow Flycatchers at Fish Creek, and for mentoring me over the years. I would like to acknowledge the Utah State University Ecology Center and the USU Department of Biology for providing financial, logistical, and intellectual support. Research funding was also generously provided by the US Geological Survey, Colorado Plateau Research Station; the U.S. Bureau of Reclamation, Salt Lake City office; the American Museum of Natural History’s Frank M. Chapman Fund; and the USU Claude E. ZoBell Scholarship. I am grateful to the USU Department of Biology and USU ADVANCE for providing me with graduate teaching and research assistantships during my time at USU. Thank you to the Manti-La Sal National Forest for allowing me to conduct my field research at Fish Creek and to the Utah Division of Wildlife Resources and especially Frank Howe for supporting my research with Willow Flycatchers. Over the years, many people provided field and laboratory assistance. This study would not have succeeded without the help, camaraderie and good humor of John Goodell, Megan Kanaga, and Ben Christiansen. Working with stable isotope and fecal sample analysis provided additional challenges and I am grateful for the expertise of Toby Hooker, Sarah Clarke, and James Pitts.

Graduate school has been a wonderful time in my life, and Utah State University was an ideal place for me to attend school. Thank you to an amazing community of graduate students and friends for providing social and recreational outlets including Koren Nydick, Greta Burkart, Brad Brandewie, Chris Arp, Heidi Nielsen, Megan Kanaga, Brian Creutzberg, and Teresa Lorenz.
On my very first day of graduate school, I met Ian McAlexander who quickly became my best friend and eventually my husband. Ian, thank you for providing me with love, support, and empathy over the past eight years. My sister Marielle has served as my confidant, best friend, and personal stylist throughout graduate school, thanks sista! I am grateful for my parents and extended family for their constant encouragement. Finally, although it occasionally served as a hindrance, thank you Mother Nature for the epic snow!

Amanda V. Bakian
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CHAPTER 1
INTRODUCTION

Spatial heterogeneity is a common feature of the natural world. Understanding the spatial context of ecological patterns and processes continues to be an important goal in ecology. Animals respond to spatial heterogeneity on multiple scales (Wiens 1989) and individual level responses impact population and community-level dynamics (Kareiva 1990). Perhaps most importantly, it is environmental heterogeneity over space and time that creates niche space, promotes species diversity (MacArthur and MacArthur 1961, MacArthur 1964) and community stability (Huffaker 1958, May 1974), and enables the coexistence of species (Holt 1984, Levin 1992). Ecologists have assembled a considerable amount of empirical evidence establishing the link between spatial pattern and ecological process. For example, spatial heterogeneity has been found to impact species-level dispersal patterns (Morales and Ellner 2002, Bonte et al. 2006, Merckx and Van Dyck 2007), the use and availability of refugia (Gilinsky 1984, Kauffman et al. 2007), predator/prey dynamics (Oksanen and Henttonen 1996, Thies et al. 2003, Bonoit-Bird and Au 2003), reproductive fitness (Palmer 1995, Nilsen et al. 2004), and animal space use (Kie et al. 2002).

Although the ecological theory of spatial heterogeneity was well developed by the end of the 20th century, experimental tests of the theory were implemented at a slower pace (Legendre and Fortin 1989, Doak et al. 1992). For years, the spatial variation of natural populations and communities and the resources on which they depend were typically assumed to follow a uniform distribution over space and time (Pickett and Cadenasso 1995). Starting in the 1980’s, the incorporation of space into applied ecology resulted in a number of key papers (e.g. Legendre and Fortin 1989, Turner 1989, Wiens 1989, Kareiva 1990). The ideas championed in these papers eventually lead to the development of landscape ecology as a sub-discipline of ecology (Turner 1989, Wiens 1989, Turner et al. 2001). Landscape ecology emphasizes the ecological causes and

At the same time that landscape ecologists were promoting the paradigm that spatial heterogeneity is a driver of ecological phenomenon, quantitative and statistical ecologists were making progress with incorporating spatial variation into statistical models. Legendre and Fortin (1989) was one of the first papers to address the general inferential problems that spatially autocorrelated data introduces to ecological analyses when it goes uncontrolled. Statistical models formulated from spatially autocorrelated data in which the spatial dependency in the data is ignored typically suffer from residual spatial autocorrelation leading to deflated parameter standard errors, increased type I errors, and erroneous inference (Lennon 2000, Aarts et al. 2008). In recent years, numerous analytical techniques have been introduced and used by researchers to satisfy statistical assumptions of independence of errors in the presence of spatial autocorrelation including wavelet-revised generalized linear regression (Carl and Kühn 2008), conditional and simultaneous autoregressive models (Lichstein et al. 2002), lagged-predictor models (Florax and Folmer 1992), autologistic models (Augustin et al. 1996), generalized estimating equations (Carl and Kühn 2007), and generalized linear mixed models with spatial random effects or spatially dependent error covariance (Diggle et al. 1998). In addition, the increasing use of Geographic Information Science by ecologists has further facilitated the incorporation of spatial structure into ecological analysis. Despite progress in developing spatially-explicit statistical models, some debate remains over how vital consideration of spatial autocorrelation is in some statistical models (Diniz-Filho et al. 2003, Hawkins et al. 2007).

These two concepts, understanding the impact of spatial heterogeneity on ecological processes and appropriately modeling spatial structure, are growing increasingly important as the natural world undergoes widespread human-induced change resulting in greater numbers of wild
populations requiring active management for conservation. The Willow Flycatcher, *Empidonax traillii*, is one such species whose long-term population viability is challenged by habitat alteration. While spatial heterogeneity may impact many aspects of the Willow Flycatcher’s ecology, I investigate the influence that spatial heterogeneity has on their individual and population-level dynamics. More specifically, I focused on exploring Willow Flycatcher’s space use, resource selection and food web responses to spatial heterogeneity.

The Willow Flycatcher is a small, neo-tropical migrant that breeds in dense riparian habitat throughout the continental United States (Fig. 1.1). In the western United States, the species has experienced population declines due largely to habitat modification and destruction and due to nest parasitism by the Brown-headed Cowbird (Sedgwick 2000). The Southwestern Willow Flycatcher, *Empidonax trailli extimus*, is a federally listed endangered species (US Fish and Wildlife 1995). Other sub-species of Willow Flycatcher are facing similar declines in the western U.S. Understanding resource selection and space use in the Willow Flycatcher is important for its active management and conservation. In addition, Willow Flycatchers are conspicuous throughout their range and are easy to identify through sight and song making them an ideal model species for hypothesis testing.

In chapter 2 of my dissertation, I investigate Willow Flycatcher’s foraging and vocalization resource selection using Bayesian spatial generalized linear models. Behavior is often overlooked in habitat selection studies (Lima and Zollner 1996) although the distribution of behavior on a landscape reflects the underlying spatial pattern of resources important to a species. I model foraging and vocalization behavior separately to test the hypothesis that behavior is spatially segregated in the home ranges of Willow Flycatchers. By doing so, I produced separate probability maps of foraging and vocalization behavior in Willow Flycatcher home ranges which may be viewed as “behavioral landscapes”. The modeling approach presented in chapter 2 is novel yet amenable to most resource selection analyses. Another goal of chapter 2 is to
demonstrate the general utility of this modeling approach to analyzing behavioral animal resource selection.

Fig. 1.1. Breeding range of the four recognized Willow Flycatcher sub-species in the continental U.S.

In chapter 3, I test hypotheses concerning the use of aquatic versus terrestrial insects by the Willow Flycatcher. Food resources vary spatially and temporally over the course of the Willow Flycatcher’s breeding season at Fish Creek. In addition, habitats vary in their insect productivity and arthropods emerging from more productive habitats may move into adjacent, less productive habitats. Willow Flycatchers inhabit the riparian zone that buffers open water and terrestrial environments. Past studies of the flycatcher diet indicate that flycatchers may require prey resources produced outside of the riparian zone during the breeding season (Wiesenborn and Heydon 2007). I measured the contribution of aquatic and terrestrial insects to the diet of Willow Flycatchers using carbon and nitrogen stable isotopes and fecal sample dissection. In addition, I
compared the diet of Willow Flycatchers at Fish Creek, Utah with the diet of Willow Flycatchers from previously published studies.

In chapter 4, I compare and contrast space use metrics in two populations of Willow Flycatcher, *E. t. extimus*, commonly known as the Southwestern Willow Flycatcher (SWFL), and *E. t. adastus*, commonly known as the Willow Flycatcher (WIFL). Although Willow Flycatchers appear to be in decline throughout much of their range in the western United States, the SWFL sub-species, a federally-listed endangered sub-species, has received most of the research attention and little is known about other populations of Willow Flycatchers. Information collected on the Southwestern Willow Flycatcher may be used to manage non-SWFL populations yet the suitability of SWFL ecology to WIFL populations is largely unknown. I hypothesized that flycatchers at Roosevelt Lake, Arizona maintain smaller home ranges and core areas than flycatchers at Fish Creek, Utah due to differences in the structure and composition of habitat patches between these two sites. In addition, I expected to find differences in space use metrics as a function of flycatcher breeding status and sex.

In the final chapter of my dissertation, I summarize the studies’ major findings and discuss the implications of these findings on the conservation and management of the Willow Flycatcher, and on landscape and spatial ecological theory. In addition, I suggest future research needs based on this study’s primary findings.

LITERATURE CITED


CHAPTER 2
IDENTIFYING SPATIAL PATTERNS OF BEHAVIOR IN WILLOW FLYCATCHERS, 
*EMPIDONAX TRAILLII*, USING BAYESIAN RESOURCE SELECTION FUNCTIONS\(^1\)

ABSTRACT

Animal resource selection is a complex, hierarchical decision-making process. Resource selection studies often focus on the presence and absence of an animal rather than the animal’s behavior at resource use locations. In this study, we investigate foraging and vocalization resource selection in a population of Willow Flycatchers, *Empidonax traillii adastus*, using individual and population-level Bayesian spatial generalized linear models. Radio telemetry locations were collected from 35 adult Willow Flycatchers (\(n = 14\) males, \(n = 13\) females, and \(n = 8\) unknown sex) over the 2003 and 2004 breeding seasons at Fish Creek, Utah. Results from the 2-stage modeling approach indicate that habitat type, perch position, and distance from the arithmetic mean of the home range (in males) or nest site (in females) were important factors influencing foraging and vocalization resource selection. Parameter estimates from the individual-level models indicated high intraspecific variation in the use of the various habitat types and perch heights for foraging and vocalization. Foraging was found to have a larger effective range of spatial dependency than vocalization based on the average estimated value of the individual-level model’s spatial decay parameter. Male flycatchers were observed to have a larger effective range of spatial dependency than female flycatchers for foraging and vocalization. On the population level, Willow Flycatchers selected riparian habitat over other habitat types for vocalizing but used multiple habitat types for foraging including mountain shrub, young riparian and upland forest. Mapping of observed and predicted foraging and vocalization resource selection indicates that the behavior often occur in disparate areas of the home range. This

\(^1\) Coauthored by Bakian, A.V., K.A. Sullivan, and E.H. Paxton
suggests that multiple core areas may exist in the home ranges of individual flycatchers. We discuss the management implications of individual-level heterogeneity versus population-level inference on Willow Flycatcher conservation and management.

1. Introduction

A paramount objective of ecology is to understand not only where organisms exist but also to understand why (Krebs, 1978). Despite increasingly sophisticated technology available to study animal resource selection and use, we remain largely ignorant about the motivations of animals when selecting resources. Inference based on studies of resource selection would greatly improve if resource selection incorporated behavior rather than mere presence (Lima and Zollner, 1996; Marzluff et al., 2001).

Closely aligned with animal resource selection is the field of animal space use. Identifying the home range, the area an organism uses to fulfill its breeding, foraging and survival needs (Burt, 1943), is often the focal point of animal space use studies. When an animal’s daily activity is largely restricted to its home range, we may infer that the home range contains the majority of resources required by an animal for breeding and survival. Hence, the home range serves as the natural spatial boundary within which to examine resource selection (Marzluff et al., 2004).

Within the home range, space use patterns rarely follow a uniform distribution and animals typically show a tendency to use certain parts of their home ranges more frequently than other parts (Hayne, 1949). The disparate use of parts of the home range reflects the spatially segregated nature of the resources important to an organism. Areas of intensive use within the home range are known as core areas. Most space use studies focus on delineating a single core area within an individual’s home range (Laver and Kelly, 2008) although multiple core areas may exist. If so, across these multiple core areas resource selection may vary as a function of behavior indicating that particular core areas are used for unique behavior. For example, Marzluff et al. (2001),
recommends constructing behavioral-specific kernel utilization distributions to look for
differential space use for foraging, locomotion, perching and parental care behavior in the
American Crow. Their analysis found that the most frequent behavior of crows’ (ie, perching and
foraging) was spatially segregated.

Resource selection is a complex, hierarchical decision-making process. Most studies of
resource selection compare landscape and habitat attributes at used locations with attributes at
either available or unused locations using popular resource selection function (RSF) modeling
approaches such as categorical analysis (Neu et al., 1974), discrete choice models (Cooper and
Millspaugh, 1999, 2001), compositional analysis (Aebischer et al., 1993), or logistic regression
(Manly et al., 2002). In this study, we show how resource selection can be analyzed as a
hierarchical process by formulating behaviorally and spatially-explicit Bayesian resource
selection functions with random effects to investigate and predict vocalization and foraging
behavior in Willow Flycatchers at individual (home range level) and population-levels. We chose
to set our multi-level RSFs in a Bayesian framework for a number of reasons. First, hierarchical
relationships are easily specified in Bayesian models and given the hierarchical nature of resource
selection, the Bayesian framework naturally lends itself well to modeling RSFs. Second,
Bayesian procedures also provide a straightforward way to include random effects in generalized
linear models. Third, Bayesian inference is based on interval estimation and not on large-sample
theory, and Bayesian inference is less sensitive to the influence of sample sizes than are
frequentist significance tests.

The Willow Flycatcher, *Empidonax traillii*, is a small, neotropical migrant that selects
riparian habitats for breeding throughout the continental United States. They are territorial and
central place foragers (Orians and Pearson, 1979; Stephens and Krebs, 1986). Male flycatchers
sing and defend territories from tall perches (McCabe, 1991). The majority of research on the
Willow Flycatcher has focused on male flycatchers due to their easier detectability. Research
indicates however that male and female flycatchers show variation in their habitat preferences for breeding and nest site selection (Sedgwick and Knopf, 1992) suggesting that it is critical to incorporate both sexes into research studies aimed at deriving population-level inference. Willow Flycatchers are a riparian-habitat obligated species (Sedgwick, 2000), yet circumstantial evidence exists to suggest that they may rely on a diversity of habitat types to meet their resource needs during the breeding season. The degree to which Willow Flycatchers use non-riparian habitats during the breeding season remains largely unknown. By measuring resource selection as a function of specific behavior, we hope to gain an understanding of when and why Willow Flycatchers use alternative habitats.

Our study integrates statistical modeling and GIS to estimate home ranges, visualize flycatcher vocalization and foraging behavior, and produce images of spatial predictions of flycatcher resource selection. In addition, in response to the wide-spread use of arbitrary core area delineators such as the 50% kernel utilization distribution, we will demonstrate the utility of our modeling approach for delineating behaviorally specific core areas and for identifying spatially segregated behaviors within the home range. Our study’s primary objectives are: 1) demonstrate the utility of modeling animal resource selection in a spatially and behaviorally explicit Bayesian RSF framework, 2) investigate differences in Willow Flycatcher foraging and vocalization resource selection between male and female flycatchers at the individual and population scale, 3) examine the degree of spatial segregation in foraging and vocalization behavior in the home ranges of Willow Flycatchers, and 4) elucidate differences in the use of various habitat types for foraging and vocalization.
2. Methods

2.1 Study site

This study was conducted along a three-mile stretch of the Fish Creek drainage in Manti-La Sal National Forest, Carbon County, Utah (Fig. 1; 39°77’ N, 111°20’ W). Fish Creek is a perennial high elevation (~2560 m) creek that drains the Wasatch Plateau from west to east into Scofield reservoir and contains the highest density of Willow Flycatchers in Utah (Frank Howe, personal communication). Within the floodplain, Fish Creek is composed primarily of young and mature riparian vegetation that is dominated by willow shrubs (*Salix* spp.), growing in a series of patches along the stream corridor. Herbaceous vegetation, open water (creek and beaver ponds) and upland habitat types border the riparian patches. Upland habitats with north facing aspects are composed of forests dominated by Englemann’s spruce (*Picea engelmanni*), White fir (*Abies concolor*), Douglas fir (*Pseudotsuga menziesii*), and Quaking aspen (*Populus tremuloides*) species. Upland habitats with south facing aspects are composed of a mixture of mountain shrub and desert shrub steppe vegetation dominated by big sagebrush (*Artemisia tridentate* sp.), Utah serviceberry (*Amelanchier utahensis*), chokecherry (*Prunus virginiana*), mountain snowberry (*Symphoricarpos oreophilus*) and various shrubsteppe grasses (Table 2.1).

2.2 Field data collection

Data was collected over the 2003 and 2004 breeding seasons during which the population size of flycatchers along the five mile stretch of Fish Creek studied was stable (n ~ 50; Bakian, unpublished data). From the approximately 25 territories established per year, fifteen territories were selected annually from which to sample flycatchers. Willow Flycatchers were trapped using mist-nets, and birds were captured using both passive netting and target netting techniques (Sogge et al., 2001). Captured Willow Flycatchers were banded with a red-color anodized Federal bird band on one leg, and a uniquely, colored metal band on the opposite leg. Age was determined by
examining plumage, molt patterns, and skull ossification. Sex was determined based on the presence of a cloacal protuberance in males or brood patch in females, and in some cases based on wing chord and tail length (Pyle, 1997). Occasionally, sex was challenging to determine and for these individuals, their sex was recorded as unknown. After a flycatcher was banded and measured, the Holohil LB-2N radio-transmitter, was attached to the lower back of the animal using Skin-bond®, a medical adhesive (Paxton et al., 2003).

Table 2.1. Habitat type definitions at Fish Creek, Utah.

<table>
<thead>
<tr>
<th>Habitat type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mature riparian</td>
<td>Stands of mature willow (<em>Salix spp.;</em> &gt; 1 m tall) dominated vegetation found adjacent to standing water. An understory of mixed grasses and forbes is typically present. Breeding habitat for flycatchers.</td>
</tr>
<tr>
<td>Young riparian</td>
<td>Stands of shrubby, mixed vegetation found adjacent to standing water. Typically, comprised of immature willow (<em>Salix spp.;</em> &lt; 1 m tall) that may grow as isolated clumps, or as individual plants. Willows may be interspersed with other shrub species including black twin-berry (<em>Lonicera involucrate</em>), choke cherry (<em>Prunus virginiana</em>), serviceberry (<em>Amelanchier alnifolia</em>), and various forbes and grasses. Vegetation may also be interspersed with areas of bare ground.</td>
</tr>
<tr>
<td>Bare ground</td>
<td>Areas void of vegetation and comprised of bare soil, rock or sand.</td>
</tr>
<tr>
<td>Upland forest</td>
<td>Continuous stands comprised of various tree species including White Fir (<em>Abies concolor</em>), Douglas Fir (<em>Pseudotsuga menziesii</em>), Englemann’s Spruce (<em>Picea engelmanni</em>), and Quaking Aspen (<em>Populus tremuloides</em>).</td>
</tr>
<tr>
<td>Mountain shrub steppe</td>
<td>Various shrubs including but not limited to big sagebrush (<em>Artemisia tridentate</em>), choke cherry, gooseberry (<em>Ribes spp.</em>), black twin-berry, service berry, and rabbitbrush (<em>Chrysothamnus spp.</em>). Shrubs are interspersed with various forbes and grasses.</td>
</tr>
<tr>
<td>Open water</td>
<td>Areas of flowing or standing water of measurable depth.</td>
</tr>
</tbody>
</table>

2.3 Radio tracking

Radio-tracking was conducted at least four times daily for each Willow Flycatcher, within four established time periods: AM early (0600-0915), AM late (0916-1230), PM early (1231-1545) and PM late (1546-1900). All tracking was randomly assigned within each time
interval, and for the most part, the tracking efforts were evenly distributed across all four intervals for each bird with a goal of collecting at least 30 radio locations per bird. Equipment used in tracking included R-1000 Telemetry receivers manufactured by Communications Specialists, Inc. and standard hand-held 3-element yagi antennas.

We used a homing-in method (Paxton et al., 2003) to pin-point the geographical position of radio-tagged flycatchers, and a radio-location was established as soon as the radio-tagged flycatcher became visible to the tracker. Occasionally, the technician caused the bird to move from its original position prior to acquiring an observation. In such cases, the tracker estimated the position of the bird before it was disturbed and used this estimate as the bird’s location. On other occasions, the radio-tagged flycatcher was heard nearby but a visual confirmation was not possible due to thick vegetation. When this occurred, both the homing-in method and an estimate of the vocalization position were used to determine the position of the bird.

Following visual confirmation of a bird’s location, the tracker recorded geographical and detailed behavioral information about the bird including the bird’s perch substrate, the bird’s position in the substrate, habitat type, and the flycatcher’s behavior. Specific behavior recorded included vocalization, foraging, nest building, territorial defensive, feeding nestlings or fledglings, and thermoregulating. Detailed vocalization and foraging behavior recorded included vocalization type (song or call) and foraging type (e.g. sally or glean). The bird’s perch height position in the vegetation was measured on a scale of low, medium or high. Six habitat types were considered at Fish Creek: mature riparian habitat (Willow Flycatcher nesting habitat), young or scrubby riparian habitat, mountain shrub, upland forest, bare ground and water (Table 2.1). The geographic location (in UTMs) and their associated accuracy measurements of each bird location were recorded using a global positioning system (GPS) device (Garmin Etrex Legend H GPS Navigator). Tracking was continued daily until the transmitter failed due to battery failure,
or the flycatcher became undetectable. All attempts were made to relocate a flycatcher when a signal was lost.

2.4 Landscape and home range analyses

We used the fixed-kernel UD with least squares cross validation for estimating individual flycatcher home ranges. Kernel UD home ranges were estimated in ArcView 3.3 using the ANIMAL MOVEMENT extension (Hooge and Eichenlaub, 1997). We limited our estimation of fixed-kernel UD home ranges to individuals for which at least 30 observations were collected to ensure accurate home range estimation (Seaman et al., 1999).

A population-level estimate of the total area used by the Willow Flycatchers over the 2003 and 2004 breeding seasons was calculated by simultaneously displaying all flycatcher home ranges and creating a polygon encompassing all home ranges while minimizing the inclusion of non-home range areas. A land cover map of Fish Creek was constructed for the landscape area encompassed by the ‘total area used’ polygon with habitat types delineated into six habitat types (listed in Table 2.1) based on a combination of field surveys and color aerial photographic images. The habitat composition of individual home ranges was determined by intersecting the home range polygons with the land cover map.

2.5 Statistical analyses

2.5.1 Conceptual model

Our analytical approach used a standard logistic regression model, with a spatial random effect added to the logistic regression model. This model was then set in a Bayesian hierarchical framework. The presence or absence of a specific behavior (e.g. vocalization or foraging) at each radio-telemetry location was treated as the response variable. The analysis was conducted at the individual and population-level in which the presence or absence of a behavior was grouped across individuals. Many of the parameters in the logistic regression models such as the
explanatory variable coefficients and the spatial random effect parameters were treated as unknown variables and were represented by distributions with pre-specified means and variances. A Metropolis-Hastings Markov chain Monte Carlo algorithm is used to produce distributions of estimates of the unknown parameters, and individual and population-level inference such as the use of mountain shrub habitat for foraging by female Willow Flycatchers is based on these distributions.

**Fig. 2.1.** Geographical location of the Fish Creek drainage in Carbon County, Utah.

### 2.5.2 Exploratory data analysis

Animal resource use locations are often autocorrelated in space and time. In many selection studies, spatial autocorrelation is overlooked and invalidates assumptions of RSF model independence and identically distributed data. In our individual-level models that investigate
vocalization and foraging selection behavior throughout the home range, we included a Gaussian process to capture the spatial variance inherent in the response and explanatory data.

Spatial autocorrelation was confirmed visually by plotting a variogram to individual flycatcher data. Variograms display the correlation in the deviations of the observations from the mean response as a function of distance between locations assuming a stationary process (an example is shown in Fig. 2.2). Variograms were fit to logistic regression models including complete sets of covariates. Individual and population-level variograms were fit separately for vocalization and foraging behaviors.

Exponential and spherical parametric spatial models without a nugget parameter were fit to the variograms using weighted least squares. The spatial models were used to find estimates of the partial sill (asymptotic point on the vertical axis) and range (asymptotic point on the horizontal axis) parameters to apply as starting points for the spatial process models in the Bayesian RSFs. The better fit spatial model (either spherical or exponential) was determined via eye-ballig and used in the spatial process component of the hierarchical model.

2.5.3 Explanatory variables

Three attributes were measured at each flycatcher observation location for inclusion in the hierarchical models: 1) categorical habitat type, 2) distance of the radio-location from the nest site (females) or arithmetic mean of the home range (males), and 3) vertical position of the bird in the vegetation. The categorical habitat type was coded as a dummy variable. In the individual-level models, the choice of reference habitat varied among models depending on the habitat types selected by the individual; not all habitat types available were used. In general, an effort was made to examine the use of mature riparian habitat (nesting habitat) for vocalization and foraging behavior versus “alternative” habitat types including mountain shrub, forest or young riparian habitats. In the individual-level models, riparian or mountain shrub habitats were
used as the reference habitats while riparian habitat served as the reference habitat in the population-level models.

The Euclidean distance (in meters) was measured from the observation to the nest site location (in the case of female flycatchers) or arithmetic mean of the home range (in the case of male flycatchers) to explore what influence central place fidelity may have on flycatcher foraging and vocalization. Finally, association between bird habitat perch position and behavioral activity were explored through the addition of habitat perch position as a model covariate. Perch position was coded as a dummy variable with three levels: low, medium or high. In the individual-level models, typically low or high served as the reference location while high served as the reference position in the population-level models.

2.6 Hierarchical Bayesian spatial model

Our hierarchical spatial model is composed of three conditional model components: a data or likelihood model \( [data|process, data \text{ parameters}] \), a process model \( [process|process \text{ parameters}] \), and a parameter model \( [data \text{ and process } \text{ parameters}] \). The likelihood model is similar to the likelihood used in traditional maximum-likelihood estimation and specifies the distribution of the observed data conditioned on both the process of interest and the data model’s parameters. The process model specifies the process of interest conditioned on its parameters, and the parameter model describes the distribution of the parameters in the data and process models. By applying Bayes’ Theorem, the posterior or joint distribution of the hierarchical model is obtained:

\[
[process, parameters|data] \propto [data|process, parameters] \times [process|parameters][parameters].
\] (1)

Alternatively, the joint posterior distribution can be represented as
where, $\phi$ represents the process model, and $\Theta$ represents the unknown parameter vector. The unknown parameters in $\Theta$ and the data $y$, are linked only through the process model, $\phi$.

### 2.6.1 Data and process models

Separate hierarchical models were fit to each behavior (vocalization and foraging) for each individual resulting in two models per animal. One population-level model was fit to each behavior for a total of 2 population-level models. The logistic link regression model serves as the starting framework for both the individual and population-level hierarchical models. If we sampled $i = 1, \ldots, n$ animals observing each animal at $j = 1, \ldots, m$ locations and considering only one behavior at a time (either foraging or vocalization), then, $y_{ij} = 1$ indicates the presence of behavior at location $j$ by animal $i$ and $y_{ij} = 0$ indicates the absence of that behavior. Given a response that is conditional upon a set of covariates, such as $x_{ij}$ for location $j$, we assume the $y_{ij}$’s (the data model component) follow a Bernoulli distribution, $y_{ij} \sim Ber(p(x_{ij}))$ with

$$P(y_{ij} = 1|x_{ij}) = p(x_{ij}).$$

The relationship between the response data vector $y_i = (y_{ij}, \ldots, y_{im})$, and the $m \times k$ matrix of $k$ predictor variables, $X_i = [x_{i1}^T, \ldots, x_{im}^T]$, where each $x_{ij}^T$ is the $1 \times k$ vector of covariates at the $j$-th location, the probability of use by animal $i$ of location $j$ (the process model component) is modeled as a logistic link regression,

$$p(x_{ij}) = \frac{\exp(x_{ij}^T \beta_i)}{1 + \exp(x_{ij}^T \beta_i)},$$

where $\beta_i = (\beta_{i1}, \ldots, \beta_{ik})$ is the $k$-dimensional vector of parameters for animal $i$. 

2.6.2 Modeling spatial variation

There are a number of ways to treat spatial variability in linear models (see Littell et al., 2006, chapter 11; Diggle and Ribeiro, 2007). We start by considering the form of the general linear mixed model:

\[ Y = X\beta + Z\mu + e, \]  

(4)

where, \( Y \) is the vector of observations, \( X \) is the matrix of explanatory variables or covariates, \( \beta \) is the vector of fixed effect parameters, \( Z \) is the matrix of covariates pertaining to the random factor, \( \mu \) is the vector of random effects, and \( e \) is the vector of independent and identically distributed Gaussian random errors. In the case of a generalized linear mixed model, the Gaussian model in (4) is adjusted to

\[ h(Y) = X\beta + Z\mu, \]  

(5)

where we now consider the expectation of \( Y \) (assumed to be generated from a distribution belonging to the exponential family) to be related to the mean conditional on \( \mu \) through a known link function \( h(.) \). The variance of the model described in (5) is determined by the form of the conditional likelihood.

In our spatial generalized linear model, spatial variation is incorporated as a random effect. The radio-locations are regarded in a spatial context and each flycatcher observation is spatially referenced (a 2-dimensional Easting-Northing position in our case) as \( S = \{s_{ij}, \ldots, s_{M}\} \). Our response, the presence or absence of a behavior, \( Y(s_{ij}) = 1 \) or 0, now depends on spatially-associated covariates, \( X(s_{ij}) \) at location \( s_{ij} \). Our spatial generalized linear mixed model now takes on the form,

\[ h(Y(s)) = X(s)\beta + W(s), \]  

(6)
where $W(s)$ is a random effect capturing the spatial variance in the ecological process.

Combining the logistic regression model shown in (1) with the spatial generalized linear mixed model displayed in (6) produces,

$$p(s_{ij}) = \frac{\exp\left(s(s_{ij})^T \beta_i + w(s_{ij})\right)}{1 + \exp\left(s(s_{ij})^T \beta_i + w(s_{ij})\right)}.$$  \hspace{1cm} (7)

As mentioned above, the spatial variation in the process model is captured by $W(s)$ in (6) and in (7), we find that for a collection of radio-locations, in our case, $S$, the realization of the spatial process becomes $w_i = \left(w(s_{ij})\right)_{j=1}^M$. We used a Gaussian process to model spatial variation, a popular choice for linear models due to their flexibility in characterizing spatial correlation (see Cressie, 1993; Banerjee et al., 2004). We modeled $w_i$ as a multivariate Gaussian distribution, $MVN(0, \sigma^2 I R(\phi_i))$, where $R(\phi_i) = [\rho(s_j - s_k; \phi_i)]_{k,j=1}^M$ is the $M \times M$ spatial correlation matrix, and the spatial dependence is modeled by $\rho(s - s'; \phi_i)$, a spatial correlation function belonging to the Matérn family of spatial functions. In our individual models, we choose between the spherical and exponential correlation functions. The exponential model takes the form, $\rho(s_j - s_k; \phi_i) = \exp(-\phi_i \|s - s\|)$ while the spherical model follows $\rho(s_j - s_k; \phi_i) = \left(\frac{3}{2} \|s - s\|_{\phi_i} - \frac{1}{2} \|s - s\|_{\phi_i}^3\right)$. The effective spatial range, $d_0$, of the modeled behavior process was calculated as $d_0 \approx 3/\phi_i$ (Finley et al., 2008) in the models using the exponential covariance function, and $d_0 \approx 2\sqrt{3}/\phi$ in the models using the spherical covariance function. Two parameters are required to model $w_i$, the spatial decay parameter $\phi_i$, and the spatial effect variance, $\sigma_i^2$. Returning to equation (2), we have now fully specified the posterior distribution of our individual-level hierarchical model (Table 2.2).
**Table 2.2.** Individual-level and population level Hierarchical model conditional model components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual-level</td>
<td></td>
</tr>
<tr>
<td>Data model</td>
<td>( y_{ij} \sim Ber(p(s_{ij})) )</td>
</tr>
<tr>
<td>Process model</td>
<td>( p(s_{ij}) = \frac{\exp(x_i(s_{ij})^T \beta_i + w(s_{ij}))}{1 + \exp(x_i(s_{ij})^T \beta_i + w(s_{ij}))} )</td>
</tr>
<tr>
<td>Parameters</td>
<td>( \Omega = (\beta_i, \sigma_i^2, \phi_i, w_i) )</td>
</tr>
<tr>
<td>Population-level</td>
<td></td>
</tr>
<tr>
<td>Data model</td>
<td>( y_{ij} \sim Ber(p(x_{ij})) )</td>
</tr>
<tr>
<td>Process model</td>
<td>( p(x_{ij}) = \frac{\exp(x_i^T \beta_i + y_{0i})}{1 + \exp(x_i^T \beta_i + y_{0i})} )</td>
</tr>
<tr>
<td>Parameters</td>
<td>( \Omega = (\beta_{0i}, \beta_i^*, \sigma_i^2, y_{0i}, \epsilon) )</td>
</tr>
</tbody>
</table>

2.6.3 *Population-level model*

On a population-level, the occupancy of discrete patches by flycatchers on the landscape introduces spatial correlation that is challenging to capture statistically. Also, this form of spatial covariance dominates the finer grain spatial covariance captured in the individual level models. For these reasons, spatial covariance was not included in the population level models. Instead, individual heterogeneity is captured by the population-level models with the addition of bird-level random-effects parameter to the process model.

The process model used for the population-level inference is equation (3). In addition, a probability model for the individual random effects is added to (3) to represent the sub-populations of flycatchers randomly selected in this study from the total population of flycatchers at Fish Creek. The random bird-effects parameter takes the form \( y_{0i} \sim N(0, G) \) where \( G \) is a covariance matrix, \( G \sim W^{-1}(V, n) \). Residual error, \( \epsilon \), is assumed to follow a normal distribution.
where $\varepsilon \sim N(0, R)$ and $R \sim W^{-1}(1, 1e + 6)$. The predictor coefficients, $\boldsymbol{\beta}_{il}$, are modeled as $\boldsymbol{\beta}_{il} \sim N(\boldsymbol{\beta}_i^*, \sigma_i^2)$, for $l = 1, 2, \ldots, k$, where individual covariate estimates are calculated across all animals using independent normal distributions with common coefficient $\boldsymbol{\beta}_i^*$ and variance $\sigma_i^2$.

### 2.6.4 Prior specification

Prior distributions must be specified for the parameters included in the models. In the individual-level models, these parameters include $\boldsymbol{\Omega} = (\boldsymbol{\beta}_i, \sigma_i^2, \phi_i, \omega_i)$ with length $m+2+k$ per animal $i$. The actual length of $\boldsymbol{\beta}_i$, the $k$-dimensional vector of parameters for animal $i$, varies from individual to individual but falls within the range $3 \leq k \leq 6$ when including the intercept. We specified independent, normal distributions to the $k$ fixed effect parameters so that $\beta_i \sim N(0,0,10)$ and $\sigma_i^2 \sim \text{Inv} - \chi^2(0.01,0.01)$ (chosen such that the mean is 1). Our use of a large variance parameter in $\boldsymbol{\beta}_i$ indicates our vague knowledge regarding the value of the prior. In the population-level model, the parameters were modeled similarly where $\boldsymbol{\beta}_{il} \sim N(\boldsymbol{\beta}_i^*, \sigma_i^2)$. The spatial parameter, $\sigma_i^2$, received an inverse-Gamma distribution, $\sigma_i^2 \sim IG(a_\sigma, b_\sigma)$, and we chose to fix $a_\sigma = 2$ which gave the distribution an infinite variance with a mean of $b_\sigma$. The spatial decay parameter was given a uniform distribution, $\phi \sim U(a_\phi, b_\phi)$ where $a_\phi = 3/2000$ and $b_\phi = 1$. The posterior distribution for the individual-level models, given the specification of the conditional model components, now takes on the form:

$$p(\Omega|\text{Data}) \propto p(\phi)p(\boldsymbol{\beta})p(\sigma^2)p(\mathbf{w}|\sigma^2, \phi) \times L(\Omega; \text{Data}),$$

where $L(\Omega; \text{Data})$ is the likelihood of the data given the parameter set.
2.6.5 Posterior sampling and convergence diagnostics

We used the ‘spBayes’ (Finley et al., 2009; http://cran.r-project.org/) and the MCMCglmm (Hadfield, 2009; http://cran.r-project.org/) packages in R, for model specification, posterior sample generation and posterior prediction. Marginal posterior distributions were generated from a Metropolis-Hastings Markov chain Monte Carlo algorithm following model specification. The coefficients calculated from a non-hierarchical fitted logistic regression model served as the candidate values for the $\boldsymbol{\beta}$ parameters in the hierarchical models. In the individual-level models, candidate values for the mean ($b_o$) of the spatial parameter, $\sigma_t^2$, and the spatial decay parameter were taken as the sill and the range on the vertical and horizontal axes of the empirical variogram, respectively. The parameter tuning values were adjusted to maintain healthy acceptance rates between 23%-50% (Gelman et al., 2004). We generated multiple independent chains for each model with 75,000 iterations discarding the initial 25,000 samples as burn-in. Of the remaining 50,000 iterations, we thinned every 25th sample, and therefore posterior distributions, parameter estimates and prediction are based on 2,000 iterations. Density estimate and trace plots of the chains were produced by the Convergence Diagnostics and Output Analysis for MCMC (CODA) package in R (Plummer et al., 2009). Only chains in which healthy acceptance rates were maintained were used for inference.

2.6.6 Model selection

We used a multi-step approach for selecting individual-level behavior models as follows. First, the simplest model was fit for each individual and for each behavioral response. The Metropolis-Hastings algorithm was then used to generate the marginal posterior distributions for each parameter in the model. Following successful model convergence, distributions of the simulated marginal posterior distributions were inspected to ensure that marginal posterior distributions were sensible and congruent with the prior distributions (Fig. 2.3).
Fig. 2.2. Process used to observe and estimate the spatial autocorrelation present among a flycatcher’s radio telemetry locations. First, radio-locations are projected on to aerial photographs (pink points) and the home range is estimated as a two-dimensional 95% utilization distribution (UD, black outline) using a fixed-kernel estimator (a). The distribution of vocalization and foraging behavior is clearly observed when viewing their locations separately; in this example, foraging behavior is represented by blue points, vocalization behavior is represented by red points, and the absence of either behavior is represented by transparent points (b). Spatial autocorrelation is observed by plotting behavioral response specific variograms for vocalization (c) and foraging (d) where the x-axis represents distance between radio locations and the y-axis represents semi-variance.

Next, marginal parameter distributions were used to produce images of the fitted response to compare with images of the observed response to look for discrepancies between the observed and simulated data thereby validating the model thru graphical posterior predictive checks (Gelman et al., 2004, section 6.4). After visually examining the fit of the simplest models, additional covariates were added to the model to try to improve the fit between the observed and
the posterior simulated data. Marginal posterior samples were re-simulated via the Metropolis-Hastings algorithm, and the distribution of the posterior samples and images of the fitted response versus the observed response were again examined. This process was repeated until graphical posterior predictive checks were optimized. In other words, the models from which posterior samples of the fitted response most closely resembled the observed response were selected as the optimal individual models (see Fig. A.1 for example). The average individual selection parameter estimates and the average individual selection parameter estimate standard errors were computed and the average individual selection parameter estimate values standard errors were estimated by

\[
\sqrt{\frac{\sum_{i=1}^{m}(\bar{y}_i - \bar{y}_0)^2}{n(n-1)}}
\]

where \( n \) is the number of animals.

### 2.7 Prediction

After satisfactory samples of the parameter’s posterior distributions were acquired, \( p(\Omega|Data) \), the presence or absence of behavior, \( p(y_0(s_0)) \) was predicted throughout an individual’s home range, where \( s_0 \) represents locations with known covariate values and \( y_0 \) represents the unknown response. For prediction purposes, we pursue a posterior predictive distribution with the specification:

\[
p(y_i(s_0) = 1|y, x, x(s_0)) = \int p(y_i(s_0) = 1|\Omega, y, x(s_0)) p(\Omega|y, x)d\Omega,
\]

where \( x(s_0) \) represents a known vector of covariates at locations \( s_0 \). We created evenly spaced point grids throughout an individual’s home range and derived a vector of covariates associated with each location in the grid. A predictive sample of use probabilities was then computed at
each grid location by composition sampling by $p \left( y_j(s_0) = 1|\Omega^j, y, x(s_0) \right)$ for $j = 1, \ldots, M$ (refer to Finley et al., 2008). The posterior mean and standard deviation values from the predictive distribution at each grid location were used to create home range habitat use probability maps for each individual and each behavior (see Appendix, Fig. 1 for example). Posterior prediction distributions were not generated for the population-level models.

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**Fig. 2.3.** Marginal posterior distributions of WIFL 1 vocalization behavior model parameters: intercept, riparian, distance, high, $\sigma^2$, and $\phi$.

**3. Results**

**3.1 Radio telemetry**

For the 35 Willow Flycatchers (female $n$= 13, male $n$ =14, and unknown sex $n$ =8) radio-tagged and tracked over the 2002 and 2003 breeding seasons at Fish Creek, the total number of radio telemetry locations per individual ranged from 5-95 with an average of 39.5 locations/bird.
Individual home ranges were found to encompass different combinations and varying proportions of all six habitats (Table 2.3), with riparian and mountain shrub habitat types composing the majority of the home ranges. Home range size varied among individuals and the combined area of home ranges over the 2 years covered 63.4 hectares (Table 2.3). Male flycatcher’s home ranges (mean = 2.6 ha, SD = 1.8) were slightly larger on average than female home ranges (mean = 2.2 ha, SD = 2.6), however the differences are not statistically significant [t(25) = 0.430, p = .67 (two-tailed)].

### 3.2 Individual-level models

Forty-seven individual-level Bayesian generalized linear spatial models were formulated for flycatchers with sample sizes ≥ 24 observations/individual: 24 vocalization and 23 foraging models. Parameter estimates from the individual-level vocalization models show variation across individuals in their sign and magnitude (Fig. 2.4). This, along with the relatively large size of the standard errors of the average individual selection parameter estimates (column 7, Table 2.4) indicates intraspecific variation in the use of habitat types and perch positions by flycatchers for vocalization. The distributions of the mountain shrub and low perch position parameter estimates indicate that the majority of flycatchers do not select mountain shrub habitat or low perch position for vocalization. Overall, the average value of the individual selection parameter estimates ($\hat{\beta}_{il}$) and the median value of the parameter estimates are in concordance (Fig. 2.4 and Table 2.4). The exception is the low perch position variable which has a negative median value but an average individual value just slightly above zero ($\hat{\beta}_{il} = 0.016$). This discrepancy does not impact inference because both the median and average individual low perch position values are essentially zero. The average values of the individual selection parameter estimates suggest that across the population flycatchers select riparian ($\hat{\beta}_{il} = 3.544$) and young riparian ($\hat{\beta}_{il} = 0.506$) habitats and mid ($\hat{\beta}_{il} = 3.183$) and high perch ($\hat{\beta}_{il} = 0.630$) positions for vocalization relative to
mountain shrub habitat ($\beta_{lt} = -1.274$) and low perch position ($\beta_{lt} = 0.016$). The average individual selection parameter for distance indicates that the probability of vocalizing decreases with increasing distance from center of the home range (males) or nest site location (females), ($\beta_{lt} = -0.001$). Finer scale patterns emerge when resource selection is broken down by flycatcher sex (Fig. 2.6). Intraspecific variation in the use of young riparian habitat for vocalization appears to be driven by male’s, but not female flycatcher’s, selection of young riparian habitat. Both males and females select riparian habitat for vocalization, and female flycatchers show more variation in their use of low perch positions for vocalizing than males. The average individual selection distance parameter in the vocalization models is positive for females ($\beta_{lt} = 0.035$) but negative for males ($\beta_{lt} = -0.037$).

![Boxplots of individual parameter estimates for each model covariate (intercept, mountain shrub, riparian, young riparian, distance, low, mid and high) by behavior: vocalization (top panel) and foraging (bottom panel). Boxes indicate first and third quartiles with median shown as a line in the box. Dashed lines extend to ±1.5 times the interquartile range from first and third quartiles. Individual points represent outliers.](image-url)
Table 2.3. Willow Flycatcher home range habitat availability (proportion of home range) and home range size.

<table>
<thead>
<tr>
<th>Willow Flycatcher</th>
<th>Bare ground</th>
<th>Forest</th>
<th>Mountain shrub</th>
<th>Riparian</th>
<th>Open water</th>
<th>Young Riparian</th>
<th>Home range size (ha)</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>0</td>
<td>0</td>
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<td>0.000</td>
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<td>37</td>
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<td>0.485</td>
<td>0.247</td>
<td>0.006</td>
<td>0.158</td>
<td>1.004</td>
</tr>
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<td>Total</td>
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<td>0.265</td>
<td>0.432</td>
<td>0.137</td>
<td>0.051</td>
<td>0.102</td>
<td>63.424</td>
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Table 2.4. Population-selection parameter estimates and standard errors.

<table>
<thead>
<tr>
<th>Covariate</th>
<th>$\beta_i$</th>
<th>SE</th>
<th>95% HPD interval lower bound</th>
<th>95% HPD interval upper bound</th>
<th>Average value of individual selection parameter estimate</th>
<th>SE of average individual selection parameter estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vocalization</strong></td>
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<tr>
<td>Intercept</td>
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<td>1.127</td>
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<td>-2.893</td>
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<td>NA</td>
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<tr>
<td>Mountain shrub</td>
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<td>-1.137</td>
<td>-0.224</td>
<td>-1.274</td>
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<td>Riparian</td>
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<td>NA</td>
<td>NA</td>
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<tr>
<td>Young riparian</td>
<td>-0.531</td>
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<td>-0.917</td>
<td>-0.140</td>
<td>0.506</td>
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<td>NA</td>
<td>NA</td>
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<td>0.020</td>
</tr>
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<td>Low</td>
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<td>-1.251</td>
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<td>Mid</td>
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<td>-0.867</td>
<td>-0.161</td>
<td>3.183</td>
<td>1.900</td>
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<tr>
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<td>NA</td>
<td>NA</td>
<td>0.630</td>
<td>1.048</td>
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<tr>
<td><strong>Foraging</strong></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>-1.300</td>
<td>0.006</td>
<td>-1.678</td>
<td>-0.944</td>
<td>-4.160</td>
<td>1.257</td>
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<tr>
<td>Forest</td>
<td>1.415</td>
<td>0.017</td>
<td>0.277</td>
<td>2.534</td>
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<td>NA</td>
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<tr>
<td>Mountain shrub</td>
<td>2.121</td>
<td>0.007</td>
<td>1.663</td>
<td>2.567</td>
<td>3.389</td>
<td>1.027</td>
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<tr>
<td>Riparian</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>-0.712</td>
<td>1.235</td>
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<tr>
<td>Young riparian</td>
<td>1.408</td>
<td>0.006</td>
<td>1.002</td>
<td>1.817</td>
<td>1.939</td>
<td>0.665</td>
</tr>
<tr>
<td>Distance</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.024</td>
<td>0.017</td>
</tr>
<tr>
<td>Low</td>
<td>-0.900</td>
<td>0.006</td>
<td>-1.308</td>
<td>-0.484</td>
<td>-0.088</td>
<td>1.524</td>
</tr>
<tr>
<td>Mid</td>
<td>-0.542</td>
<td>0.005</td>
<td>-0.911</td>
<td>-0.169</td>
<td>1.826</td>
<td>0.944</td>
</tr>
<tr>
<td>High</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>4.819</td>
<td>1.354</td>
</tr>
</tbody>
</table>
Different patterns in resource selection are inferred from the individual-level foraging models compared to the individual-vocalization models. The distributions of the individual-level parameter estimates indicate that many flycatchers select mountain shrub and high perch positions for foraging (Fig. 2.4). The distribution of riparian and young riparian habitat and low and mid perch position parameter estimates around zero as well as the relatively large magnitudes of the standard errors of the average individual selection parameter estimates (column 7, Table 2.4) suggests intraspecific variation in the use of these variables for foraging. The values of the median and average individual-selection parameters agree across variables (Fig. 2.4 and Table 2.5). The average values of the individual selection parameter estimates suggest that across the population, flycatchers select mountain shrub ($\beta_{it} = 3.389$) and young riparian habitat ($\beta_{it} = 1.939$) and mid ($\beta_{it} = 1.826$) and high perch ($\beta_{it} = 4.819$) positions for foraging relative to riparian habitat ($\beta_{it} = -0.712$) and low perch position ($\beta_{it} = -0.088$) variables. The average individual selection parameter for distance indicates that the probability of foraging increases with increasing distance from the center of the home range (males) or nest site (females), ($\beta_{it} = 0.024$). Differences in selection patterns for foraging as a function of flycatcher sex also emerge. Both males and females show intraspecific variation in the selection of mid perch position for foraging while more females select low perch positions for foraging than males (Fig. 2.7). Females show greater intraspecific variation in selecting riparian habitat for foraging while males show greater intraspecific variation in selecting young riparian habitat for foraging. The average individual selection distance parameter for both males ($\beta_{it} = 0.028$) and females ($\beta_{it} = 0.021$) is positive.

Summaries of the spatial parameter estimates are displayed in Table 2.5 and Figure 2.5. The average individual parameter estimates for the spatial decay parameter, $\phi$, are similar for vocalization and foraging (0.371 and 0.319, respectively). These estimates indicate that the
Effective ranges of spatial dependency are 13.113m and 14.898m for vocalization and foraging, respectively. There is individual-level variation in the spatial dependency parameter (Fig. 2.5) with maximum and minimum spatial dependency estimates of 45.43m and 4.63m for vocalization and 69.53m and 5.90m for foraging. The average individual spatial dependency for vocalization and foraging by sex is 13.877m and 20.180m, respectively, for males and 12.349 and 10.056, respectively, for females.

**Fig. 2.5.** Boxplots of individual parameter estimates for spatial model parameters (σ², φ, 3/ φ) by behavior: vocalization (top panel) and foraging (bottom panel). Boxes indicate first and third quartiles with median shown as a line in the box. Dashed lines extend to ±1.5 times the interquartile range from first and third quartiles. Individual points represent outliers.
3.3 Population-level models

One global population-level model was selected and fit to both the vocalization and foraging data. Riparian habitat and high vegetation perch height position were used as the reference types in the global models; the distance covariate was not included in the population-level models due to a lack of a central location on a population-level (Table 2.5).

The population-selection estimates ($\beta_i^*$ column 2, Table 2.4) for the covariates in the vocalization model show that alternative habitat types including forest ($\beta_i^* = -1.634$), mountain shrub ($\beta_i^* = -0.677$) and young riparian ($\beta_i^* = -0.531$) habitats are selected less for vocalization by flycatchers relative to riparian habitat, and low ($\beta_i^* = -0.900$) and mid ($\beta_i^* = -0.513$) perch positions are selected less by flycatchers relative to the high perch position. The 95% credible intervals for the forest, mountain shrub, young riparian, low, mid and high covariates do not overlap 0 therefore we can infer that these covariates significantly contributed to the population-level selection model fit.

Table 2.5. Spatial covariate average individual-selection parameter estimates and standard errors.

<table>
<thead>
<tr>
<th>Spatial Parameter</th>
<th>Average value of individual selection parameter estimate</th>
<th>SE of average individual selection parameter estimates</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Vocalization</td>
<td></td>
</tr>
<tr>
<td>$\sigma^2$</td>
<td>7.384</td>
<td>1.681</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.371</td>
<td>0.040</td>
</tr>
<tr>
<td>$3/\phi$</td>
<td>13.113</td>
<td>2.469</td>
</tr>
<tr>
<td></td>
<td>Foraging</td>
<td></td>
</tr>
<tr>
<td>$\sigma^2$</td>
<td>11.755</td>
<td>2.624</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.319</td>
<td>0.034</td>
</tr>
<tr>
<td>$3/\phi$</td>
<td>14.898</td>
<td>3.289</td>
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</table>
The population-selection estimates ($\beta_i^*$ column 2, Table 2.4) for the covariates in the foraging model show that multiple habitat types are selected by flycatchers for foraging and, more specifically, alternative habitat types including forest ($\beta_i^* = 1.415$), mountain shrub ($\beta_i^* = 2.121$) and young riparian ($\beta_i^* = 1.408$) habitats are selected by flycatchers for foraging relative to riparian habitat. Also, low ($\beta_i^* = -0.900$) and mid ($\beta_i^* = -0.542$) perch positions are selected less by flycatchers than the high position for foraging. The 95% credible intervals for the forest, mountain shrub, young riparian, low, mid and high covariates do not overlap 0 therefore we infer that these covariates significantly contributed to the population model’s fit.

The population-selection covariate estimates ($\beta_i^*$ column 2, Table 2.4) and the average individual selection covariate estimates ($\hat{\beta}_{it}$ column 6, Table 2.4) show high accordance overall with some disagreement occurring in coefficient magnitude and sign. More specifically, in the vocalization and foraging model, the population-level coefficient estimate for selection of mid perch position is negative ($\beta_i^* = -0.513$ and -0.542, respectively) while the average individual selection coefficient is positive ($\hat{\beta}_{it} = 3.183$ and 1.826, respectively). Some discrepancy in magnitude and sign between $\beta_i^*$ and $\hat{\beta}_{it}$ is not surprising given variation in the reference variables used in the individual-level models and differences in model formulations between the individual-level models and the population-level models.

Mean and standard deviation predicted vocalization values vary from 0.16-0.98 and 0.09-0.5 respectively, and mean and standard deviation predicted foraging values vary from 0.02-0.98 and 0.12-0.50 respectively (prediction image examples are presented in the Appendix, Fig. A.2).

4. Discussion

The Bayesian modeling approach presented here is mechanistic based, and provides a powerful approach to analyzing spatially and behaviorally explicit animal resource selection data. In our investigation, we related ecological pattern with process and explored Willow Flycatcher
resource selection to examine not only where vocalization and foraging behavior occurs but why. In the process, we produced continuous two-dimensional GIS surfaces depicting a flycatcher’s probability of using space for vocalization or foraging throughout its home range. These selection surfaces can be interpreted as flycatcher behavioral landscapes. In addition, although Willow Flycatchers are a relatively well studied species, this is the first study to examine spatially and behaviorally explicit resource selection in the species.

**Fig. 2.6.** Boxplots of individual parameter vocalization estimates (intercept, mountain shrub, riparian, young riparian, distance, low, mid, high, $\sigma^2$, $\phi$, $3/\phi$) for male and female Willow Flycatchers. Boxes indicate first and third quartiles with median shown as a line in the box. Dashed lines extend to ±1.5 times the interquartile range from first and third quartiles. Individual points represent outliers.

### 4.1 Individual and population-level inference

In this study, we observed considerable intraspecific variation in vocalization and foraging resource selection in Willow Flycatchers, and focused on differences in resource selection.
selection between and among male and female Willow Flycatchers. Intrapopulation differences in habitat selection among male and female Willow Flycatchers were first identified by Sedgwick and Knopf (1992). They found substantial differences between song perch sites used by males and nest sites used by females and speculated that the independent selection of habitats by male and female flycatchers during the breeding season were responsible for these differences. Our study indicates that selection diversity between male and female flycatchers extend to the selection of resources for vocalization and foraging. While both male and female flycatchers appeared to select nesting habitat for vocalizing over non-nesting habitats, male flycatchers experienced greater variation in their selection of habitat types for vocalizing than female flycatchers. Conversely, female flycatchers showed more variation in their selection of habitat position for vocalization.

The images of observed and predicted vocalization behaviors further elucidate differences between male and female flycatchers in their use of space for vocalizing. Male vocalization behavior commonly occurred in tight clusters in the central area of the home range. These spatial vocalization clusters correspond to the male flycatcher’s territory or the area of its home range actively defended against conspecifics which likely contains the majority of the individual’s song perches. Images of female home range vocalization behavior do not show the same tendencies to vocalize in tight clusters in the center of their home ranges. This pattern finds additional support in the average individual-level distance coefficient which is positive for female flycatchers and negative for male flycatchers. This indicates that, in males, the probability of vocalizing decreases with increasing distance from the center of the home range. The opposite relationship holds true for females in which the probability of vocalizing increases with increasing distance from the nest site.
Fig. 2.7. Boxplots of individual parameter foraging estimates (intercept, mountain shrub, riparian, young riparian, distance, low, mid, high, $\sigma^2$, $\phi$, $3/\phi$) for male and female Willow Flycatchers. Boxes indicate first and third quartiles with median shown as a line in the box. Dashed lines extend to ±1.5 times the interquartile range from first and third quartiles. Individual points represent outliers.

We posit that discrepancies in the role of vocalization in male and female flycatchers can explain the different patterns we observed. Male vocalization commonly occurs in the form of song and is used to establish territory boundaries and attract mates, and male flycatchers typically sing from tall, exposed perches (Sedgwick, 2000). Conversely, female vocalization commonly occurs in the form of a call and is used to maintain social contact with their male mates and as distress signals. To avoid attracting the attention of potential predators during the breeding season, females vocalize from various vegetation positions and are more likely to call at distance away from their nest sites.
We also identified differences between male and females in their foraging behavior. We found evidence that males select higher positions for foraging than females. Akin to our explanation of their vocalization behavior, male’s selection of higher habitat positions for foraging may be related to visibility and their requirement to be conspicuous during the breeding season. Alternatively, perch height foraging differences may be the outcome of a resource partitioning or reduced foraging competition mechanism (MacArthur, 1958). Both male and female flycatchers appear to use multiple habitat types for foraging with the models suggesting that they select non-nesting habitats such as mountain shrub and young riparian habitats for foraging. The probability of foraging increased with increasing distance away from either the center of the home range or the nest site in male and female flycatchers, respectively.

The identification and quantification of intraspecific variation in wildlife species such as the Willow Flycatcher is critical for a number of reasons. First, there is growing empirical evidence that males and females of a species interact with and respond to the environment in distinct ways. However, in the majority of bird census and behavioral studies, males are the focal subject as they tend to be more conspicuous. If males and females act independently of one another and have different habitat and resource requirements during the breeding season, then the inference derived from male-centric studies and applied to management and conservation plans that affect the entire species is done so erroneously. We are concerned that singing males have served as the focus of the majority of Willow Flycatcher breeding season habitat and vocalization-based census studies and that the resource needs of female flycatchers have been generally disregarded. In addition, our study suggests that there is considerable variation in the use of habitats for foraging including the use of non-nesting habitats. Since male flycatchers primarily sing in riparian habitat, conservation plans derived from research focused on singing male flycatchers might mistakenly conclude that riparian habitat constitutes the only critical flycatcher habitat. Critical habitats for flycatchers during the breeding season may also include
non-nesting habitats such as mountain shrub and young riparian habitats for foraging in addition to riparian habitat for nesting. Next, the diversity in resource selection measured in this study suggests that researchers need to be careful in selecting appropriate sample sizes for future Willow Flycatcher studies. Understanding the variation in resource selection among individuals is vital given the potential link between intraspecific variation, population-level genetic diversity (Smith et al., 2001) and the potential for animal populations to respond to current and future environmental change.

We infer trends in resource selection at the population-level based on the coefficients derived from the population-level models and the average coefficient values of the individual-level models. In general, inference based on the population-level and average individual-level coefficients are congruent. On a population-level, the flycatchers at Fish Creek showed a tendency to select riparian habitats over other habitat types for vocalization, but they were more diverse in their use of a variety of habitats for foraging. More specifically, the population-level coefficients indicate that flycatchers select mountain shrub habitat relative to riparian and other habitats for foraging. On a population-level, the probability of vocalizing decreased with increasing distance from the center of the home range/nest site and the probability of foraging increased with increasing distance from the center of the home range/nest site.

The use of non-nesting habitats by Willow Flycatchers is evidence that flycatchers may depend upon a more diverse landscape to meet their foraging requirements during the breeding season. Similar patterns suggesting habitat complementation and/or supplementation (Dunning, et al., 1992) have been observed in other species (e.g. Mamo and Bolen, 1999; Tubelis et al., 2004). We posit three reasons why habitat complementation or supplementation may be important to flycatchers at Fish Creek: 1) the availability of food resources may differ in nesting versus non-nesting habitats 2) ease of foraging by flycatchers may vary in nesting versus non-breeding
habitats, and 3) flycatchers may travel distances from their nest sites to forage to avoid attracting predators.

4.2 Home range and core area implications

The images of fitted and predicted vocalization and foraging resource selection provide insight into the spatial aspects of Willow Flycatcher behavior at Fish Creek. Foraging and vocalizing appear as spatially segregated and clustered behavior in many of the images. Fig. A.3 in the Appendix provides an example of an image of fitted vocalization and foraging behavior and the spatial patterns observed in these images confirm the models’ results that resource selection is not randomly distributed within the home range. The spatially segregated pattern of space use depicted in the images suggests the existence of two distinct core areas in this individual’s home range: one used for foraging and one used for vocalization. The parameters in the spatial process model indicate that foraging behavior has a larger effective spatial range than vocalization behavior which implies that foraging core areas are expected to be larger than vocalization core areas.

We feel that these images can be used to inform our delineation of home range core areas while also providing a more detailed understanding of flycatcher space use behavior. Many studies rely on an arbitrary designation of the core area such as the 50% kernel UD. We argue that the delineation of core areas should not be arbitrary and that a more meaningful core area concept is possible. This could be accomplished by creating images of the fitted probability of a behavior within the home range and identifying the area of the home range with the highest probability of that behavior. Once the core area has been determined, the environmental attributes associated with that region can be identified and compared with the environmental factors comprising the remainder of the home range surrounding the core areas.
4.3 Advantage of the Bayesian framework

The Bayesian approach provides a rigorous framework for modeling animal resource selection. In this study, we formulated resource selection functions as defined by Manly et al. (2002) using hierarchical generalized linear mixed models. The Bayesian approach provides a number of advantages over traditional resource selection modeling approaches. First, the Bayesian framework is flexible and general enough to handle complex problems, and naturally lends itself well to modeling dependent and independent hierarchical relationships among parameters. In animal resource selection, causal relationships are hierarchical, and dependency between the data and the underlying ecological process is intrinsic. Classical generalized linear mixed models can handle hierarchical relationships however model convergence grows increasingly challenging with increasing complexity. Samples of the posterior distribution are derived from conditional probability model statements which is fairly straightforward using random walk MCMC algorithms.

In classical modeling approaches, \( X \) is treated as a constant and \( \beta \) as fixed but unknown. In our Bayesian model, the covariates, parameters and sources of uncertainty are specified using probability statements; we argue that this is a more natural way to think about the factors that influence animal resource selection. For example, in the population-level model, intraspecific uncertainty in vocalization and foraging selection was modeled through the bird-level parameter, \( \beta_{it} \sim N(\beta_i^*, \sigma_i^2) \). Additional sources of uncertainty in our models include the effect of sex or age on resource selection. We did not formulate our models to include sex or age effects however the next generation of flycatcher resource selection population models could feasibly include these additional parameters using prior distributions informed by this and other flycatcher resource studies.

In resource selection studies that compare resource use with availability, the estimate of resource availability is subjective (Erickson et al., 2001; Jones, 2001). In addition, availability is
often assumed to be constant and known although this is rarely the case (Johnson, 1980; Arthur et al., 1996), and researchers often measure availability at temporal and spatial scales congruent with the study and not at scales biologically relevant to the organism (Aebischer et al., 1993; Gates and Evans, 1998). Further, the method used to measure resource availability can have drastic impacts on the study’s inference concerning resource selection (Johnson, 1980; Porter and Church, 1987). In nature, resource availability undergoes constant fluctuations that may be better represented as a probabilistic function in a Bayesian framework than a constant and known quantity.

4.4 Alternative modeling approaches

A number of other modeling approaches provide alternative means of analyzing the relationship among behavior, resource selection and space use including discrete choice models (McCracken et al., 1998, Cooper and Millspaugh, 1999, 2001) and resource utilization functions (Marzluff et al., 2001, 2004). Both approaches are easily implemented in a Bayesian framework (e.g. Thomas et al., 2006). Discrete choice models analyze resource selection by measuring the satisfaction acquired by selecting among resources. Their strength lies in their capacity to support fluctuations in resource availability and utility which may better reflect natural situations. Thomas et al. (2006) introduced a Bayesian random effects discrete-choice model for resource selection and applied it to the analysis of caribou resource selection. Also, discrete-choice models can support non-continuous response data structures such as binary or count responses. Resource utilization functions use multiple regression techniques to associate a probabilistic measure of use, as defined by the utilization distribution, with a set of resource variables. In the context of a behavioral analysis, a Bayesian behavioral RUF would require the calculation of behaviorally specific UDs which would then be overlaid on resource maps. The RUF approach uses a continuous measure of probabilistic behavioral use as the response which fits naturally with the Bayesian way of thinking.
4.5 Model limitations and future directions

Only ecologically relevant independent variables were included in the formulation of our Bayesian resource selection functions. However, other ecologically relevant variables exist that may influence flycatcher foraging and vocalizing behavior. Model performance is expected to improve with the inclusion of additional ecologically relevant covariates. Further, the Bayesian framework enables the inclusion of information acquired from other Willow Flycatcher studies and our current models could be updated to include information from previous and future studies. As new models are formulated through the inclusion of new information and additional parameters, model comparison and selection can be conducted using deviance information criterion (DIC), the Bayesian equivalent of Akaike Information Criterion (AIC). The models we have currently formulated do not provide the final word in Willow Flycatcher vocalization and foraging behavior at Fish Creek and should be amended as more information becomes available.

The use of the posterior distribution for producing a posterior predictive distribution has been introduced here. The predictive power of the current set of models outside of Fish Creek is unknown, and due to the small sample sizes of our data, model validation was conducted by through visual inspection. In the future, the models should be validated using subsets of the current Fish Creek flycatcher dataset or using alternative Willow Flycatcher datasets.

References


CHAPTER 3
THE CONTRIBUTION OF AQUATIC AND TERRESTRIAL INSECTS TO THE DIET OF
THE WILLOW FLYCATCHER REVEALED BY CARBON AND NITROGEN STABLE
ISOTOPES AND Fecal SAMPLE DISSECTION

ABSTRACT

Willow Flycatchers are an insectivorous, riparian obligated nesting species. Aquatic
ingsects may be an essential component of the Willow Flycatcher diet during the breeding season.
We investigated the contribution of aquatic and terrestrial insects to the diet of adult and nestling
Willow Flycatchers over the course of two breeding seasons at Fish Creek, Utah using $^{13}$C and
$^{15}$N stable isotopes and fecal sample analysis. Stable isotope analysis detected differences in $\delta^{13}$C
but not $\delta^{15}$N signatures between aquatic and terrestrial insects at Fish Creek. The terrestrial insect
isotope signature was more enriched in $\delta^{13}$C than the aquatic insect isotope signature. Aquatic
insects were found to comprise approximately 1/3 of the diet of adult Willow Flycatchers and
13% of the diet of hatch year birds. Significant differences were found in $\delta^{13}$C between adult and
hatch year flycatcher feathers and hatch year flycatcher feathers were more depleted in $^{13}$C than
adult feathers. Hymenoptera and coleoptera were the most abundant and frequently occurring
arthropod orders in the fecal samples. Our study indicates that aquatic insects are an important
component of the diet of the Willow Flycatcher at Fish Creek. In addition, adult flycatchers were
found to consume a different diet to that which they feed their nestlings at Fish Creek and we
discuss potential reasons for this pattern.

Prey subsidies (sensu Polis et al. 1997) move from more to less productive habitats, and
can provide essential energy for animal consumers inhabiting areas of low productivity
(Bustamante et al. 1995, Polis and Hurd 1996). Many such resource exchanges have been
identified in the zone where streams and terrestrial riparian habitats intersect. One such example, the movement of terrestrial insects and leaf fall from the terrestrial to the aquatic environment, has long been recognized as an important source of energy to fish in aquatic environments (Cummins et al. 1973, Vannote et al. 1980, Mason and MacDonald 1982). Less focus has been directed on the opposite flow of energy from the aquatic to the terrestrial environment. Yet, more and more evidence points to the importance of aquatic derived food resources to riparian consumers including spiders (Polis and Hurd, 1995, Sanzone et al. 2003, Kato et al. 2003), lizards (Sabo and Power 2002a,b), birds (Gray 1989, 1993; Nakano and Murakami 2001; Murakami and Nakano 2002), and mammals (Strapp and Polis 2003, Fukui et al. 2006).

The flow of aquatic insect subsidies into adjacent upland habitats may be especially important in arid and semi-arid regions. For example, in Jackson and Fisher’s (1986) seminal work, they observed that 97% of the insects originating in a Sonoran desert stream were exported to terrestrial predators within the riparian food web. In the western United States, riparian habitats often support higher densities and greater diversities of animal consumers than adjacent upland habitats (Stamp 1978, Jackson and Fisher 1986, Sanzone et al. 2003). This trend may be partly due to the emergence of aquatic insects which compliment terrestrial arthropod production thereby expanding the food base available to terrestrial predators.

Although most studies investigating the contribution of food subsidies to the diets of birds have relied on observation of foraging events and identification of individual insect prey items (e.g. Gray 1993, Nakano and Murakami 2001), stable isotopes have been used to measure energy flows from aquatic systems to consumers in riparian habitats such as spiders (Sanzone et al. 2003, Akamatsu et al. 2004, Paetzold et al. 2005), and beetles and ants (Paetzold et al. 2005). The natural abundances of isotope ratios such as carbon (C) and nitrogen (N) have been used to trace the dietary origin of assimilated energy for various passerine bird species residing in tropical rain forests (Herrera et al. 2003), terrestrial deserts (Wolf and del Rio 2003), and marine (Sabat and Martinez
del Rio 2005, Sabat et al. 2006) systems but has yet to be used, to our knowledge, to track energy assimilation in birds in temperate riparian systems.

In this study, we investigate the contribution of aquatic versus terrestrial insects to the diet of the Willow Flycatcher, *Empidonax traillii adastus*, using carbon ($\delta^{13}$C) and nitrogen ($\delta^{15}$N) stable isotope values of body feathers from adult and hatch year flycatchers. The Willow Flycatcher is a neotropical migrant that breeds in riparian areas throughout the continental United States, and requires riparian habitats bordering open water for nest site selection. In the intermountain west of the United States, riparian habitats used by Willow Flycatchers are found largely in arid or semi-arid regions. Insects immigrating into the riparian zone from adjacent aquatic habitats may therefore be an essential component of the Willow Flycatcher diet.

Previous work has alluded to the reliance of Willow Flycatchers breeding in non-native, salt cedar dominated habitats on prey subsidies derived from native habitats. Nesting habitat of the Southwestern Willow Flycatcher (*E. t. extimus*), historically dominated by willow (*Salix* spp.) and cottonwood (*Populus* spp.), has largely been replaced by stands of the exotic salt cedar in the Southwestern U.S. Studies have found that although salt cedar (*Tamarix* spp.) dominated riparian habitats are used successfully for nesting, insect prey production in exotic habitats may be insufficient to support breeding flycatchers (DeLoach et al. 2000, DeLay et al. 2002, Wiesenborn and Heydon 2007). Other studies have identified few differences in the Willow Flycatcher diet as a function of native versus non-native habitat and hence concluded that Willow Flycatchers are generalist foragers (Durst et al. 2008). A common pattern across all previous Willow Flycatcher diet studies is that adult Willow Flycatchers consume a distinctive diet from the one they feed to their nestlings. Conversely, some studies have identified differences in diet between male and female adult Willow Flycatchers (Drost et al. 2003) while others have not (Durst et al. 2008). Hence, some debate still remains as to much of a generalist versus specialist forager the Willow
Flycatcher actually is. In addition, it is unknown if diet patterns identified in *E. t. extimus* are common to other subspecies.

In this paper, we investigate energy movement in the form of prey subsidies from the aquatic to the terrestrial environment by measuring Willow Flycatcher’s use of aquatic versus terrestrial insects. We use stable isotopes to establish distinct carbon (δ\(^{13}\)C) and nitrogen (δ\(^{15}\)N) signatures for the aquatic and terrestrial environments. In addition, fecal samples were collected opportunistically from adult and nestling flycatchers. We conduct a fecal sample analysis to corroborate findings from our stable isotope analysis and to compare the diet of the Willow Flycatchers in this study with the diets of Willow Flycatchers from other studies. Our three primary objectives are to: 1) determine the ratio of aquatic versus terrestrial insects utilized by Willow Flycatchers, 2) investigate differences in flycatcher diet as a function of sex and age, and 3) compare and contrast the diet of Willow Flycatchers from Fish Creek with the diet of flycatchers from other locations to ascertain the use of aquatic insects by Willow Flycatchers across studies.

**Methods**

*Field site.*-This study was conducted along a three-mile stretch of Fish Creek located east of the inflow to Scofield Reservoir in the Manti-La Sal National Forest in north central, Utah (39°77’ N, 111°20’ W) during the 2003-2005 breeding season (late May-early August). The Fish Creek drainage is composed of a variety of habitats including mature and young riparian habitat, mountain shrub steppe, upland forest, open water and bare ground. Mature and young riparian habitats are both composed primarily of willow (*Salix* spp.) differing in the ages and heights of the willow canopy. We classified areas composed of willows < 50% canopy cover and <1 meter height as young riparian habitat. At Fish Creek, mature riparian habitat is comprised of willow dominated vegetation with ≥ 50% canopy cover and occurs in discrete patches typically separated by areas of open water, bare ground, or young riparian habitat. Mountain shrub steppe habitat at Fish Creek is
found on south facing aspects and contains a diverse community of native and introduced grasses, forbes including yarrow and larkspur, and shrubs such as big sagebrush (*Artemisia tridentate* sp.), Utah serviceberry (*Amelanchier utahensis*), chokecherry (*Prunus virginiana*), and mountain snowberry (*Symphoricarpos oreophilus*). North facing aspects support mixed-conifer and aspen forests dominated by Englemann’s spruce (*Picea engelmanni*), White fir (*Abies concolor*), Douglas fir (*Pseudotsuga menziesii*), and Quaking aspen (*Populus tremuloides*) species.

**Stable isotopes.** Feather samples were collected opportunistically from May 26-August 15 during the banding process over the 2004 and 2005 breeding seasons. While the bird was in hand, we pulled approximately ten lower breast area body feathers. Studies of molting patterns have found that Willow Flycatchers molt their flight feathers on their wintering grounds (Pyle 1997) however there is considerable variation in the timing of their definitive basic body molt which can occur any time from August thru November. At Fish Creek, we observed body molt in territorial adults starting in late July/early August. For this reason, we used adult body feathers for stable isotope analysis rather than tail feathers since the latter reflects flycatcher diet on their wintering grounds. We limited our sampling of feathers in 2004 from Willow Flycatchers known to breed at Fish Creek in 2003. Body feathers were sampled from nestlings starting at ten days of age to minimize the amount of feather sheath on feather samples. Feathers were selected over other body tissues such as blood or claw to minimize the stress of the sampling procedure on the birds, and because there is a wider breath of published material concerning feather than claw stable isotope analyses.

Insect sampling was conducted in 2004 and 2005 at Fish Creek using Malaise traps. Ten malaise traps were placed along Fish Creek in a variety of habitats to capture the diversity of insect species present. Malaise traps were checked and emptied once per week, and samples were stored in 70% ethanol. Arthropods for stable isotope analysis were randomly selected from malaise trap samples across the breeding season so that the entire breeding season was evenly
sampled. We randomly selected approximately 1000 insects from Malaise samples and identified them to the lowest taxonomic level possible. In addition, insects were categorized as either aquatic or terrestrial based on life cycle. This categorization was not perfect due to variation in the lifecycle of aquatic and semi-aquatic insects. We made every attempt possible to only select those insects that could be considered terrestrial or aquatic obligates to use in stable isotope analysis for determining aquatic and terrestrial insect stable isotope signatures. We obtained fewer obligate aquatic insects from our Malaise traps than obligate terrestrial insects and therefore included all sampled aquatic adult insects in the stable isotope analysis. We randomly selected terrestrial insects to include in our stable isotope analysis from the total number of terrestrial insects identified from our malaise samples.

Feathers and insects were cleaned of dirt and surface oils using repeated washings of a 2:1 chloroform:methanol solution and then air-dried for 24 hours in a fume hood. Previous studies have found that storing arthropod samples in ethanol has little impact on $^{15}$N and $^{13}$C values (Sarakinos et al. 2002, Syväranta et al. 2008). Nitrogen and carbon isotopes in feather and insect samples were analyzed via continuous-flow isotope ratio mass spectrometry by the Utah State University Isotope laboratory. A 0.1-0.2 mg sample of feather was encapsulated in tin and analyzed with a Europa Scientific SL-2020 system. Analytical precision over all sample runs was better than 0.1‰ for both $^{15}$N and $^{13}$C. Our stable isotope results are presented in δ notation ($\delta^{15}$N and $\delta^{13}$C) as the deviation from parts per thousand (‰).

Within trophic group differences in δ$^{15}$N and δ$^{13}$C signatures (e.g. aquatic versus terrestrial insects, and adult male versus adult female versus nestling flycatchers) were examined using analysis of variance and Welch’s $t$-tests assuming unequal variances. All statistical tests were conducted in program R (R Development Core Team 2010). We used a two-source Bayesian mixing model (Parnell and Jackson 2010) to determine the relative contribution of aquatic and terrestrial insects to the flycatcher diet over the 2004 and 2005 breeding seasons. In
contrast to traditional mixing models, Parnell and Jackson’s (2010) model allows for variation in isotopic discrimination between prey items and consumer which more accurately reflects changes in stable isotope ratios across trophic levels. The prior distribution of the proportion of aquatic and terrestrial insects contributed to the flycatcher diet was assumed to follow a Dirichlet distribution. Other sources of variation in the Bayesian mixing model include the isotopic value of prey items, the isotopic fractionation value between prey source and consumer and an overall residual error term received normal distributions as priors (see Parnell and Jackson 2010). The model also includes a measure of elemental concentration of carbon in prey sources that was acquired via mass spectrometry.

Laboratory studies of isotopic discrimination between prey source and avian consumers have found that isotopic discrimination values are higher than traditionally assumed (Pearson et al. 2003, Hobson and Bairlein 2003). Negligible $\delta^{13}$C discrimination factors were historically assumed along the lines of 0‰ to 1‰. In their study of carbon isotope fractionation in Yellow-rumped Warblers, Pearson et al. (2003) observed $\delta^{13}$C changes of 1.9 to 4.3‰ ± 0.1 depending on tissue when Warblers were fed a diet comprised of 97% mealworms. Hobson and Bairlein (2003) measured $\delta^{13}$C discrimination factors of +2.7‰ in Garden Warblers fed a diet of mealworms. We used a $\delta^{13}$C discrimination factor of 2.0 ± 0.1 between insect prey and flycatcher feathers in our Bayesian mixing models based on these study’s findings. This fractionation value is on the lower end of the ranges from the studies of Pearson et al. (2003) and Hobson and Bairlein (2003) because we assume the flycatcher diet is more heterogeneous than the mealworm diet fed to the study animals.

*Diet analysis.*-Fecal samples were obtained opportunistically from flycatchers during mist-netting and banding throughout the 2003, 2004, and 2005 breeding seasons from approximately May 26-August 15. Willow Flycatchers were randomly selected for capture and radio tracking following territory establishment (n ~ 50). Birds were captured using target
(Sogge et al. 2001) and passive mist-netting techniques. Following capture, birds were sexed and weighed, and banded with a red anodized Federal bird band on one leg and an individualized color aluminum band on the other leg. Flycatchers would often deposit fecal samples either in bird banding bags or on the hand of the bander. Nestling fecal samples were obtained from nestlings aged 7-10 days when nestlings were banded with a red anodized Federal bird band on their right leg.

Fecal sample dissection has been used in Willow Flycatcher studies to reconstruct diet (Wiesenborn and Heydon 2007, Durst et al. 2008). The collection of fecal samples is a less invasive technique for sampling diet than using emetics for regurgitation of stomach contents. Studies have found strong taxonomic correlation between prey items identified through fecal sample dissection and stomach regurgitation. Some bias may be introduced in diet reconstruction with fecal samples due to the under-detection of soft bodied insects (Ralph et al. 1985, Jenni et al. 1990). In addition, stomach regurgitation samples have been found to contain a larger number of prey items on average per sample than fecal samples suggesting that a larger number of fecal samples than regurgitation samples must be acquired for accurate diet reconstruction (Poulin and Lefebvre 1995, Carlisle and Holberton 2006).

Fecal samples were stored individually in 70% ethanol in 10 ml vials. We used a Leica MZ75 with the addition of a Lumina dual light source and a Jenoptik 3.3MP Cooled CCD Firewire Color digital camera with ProgRes Capture Pro 2.5 and Auto-Montage to create 3D photographs of arthropod fragments for analyzing and identifying sample components. References used to assist in identification included Burger et al. (1999) as well as professional entomologist expertise. Insects were identified to as fine of a taxonomic scale as possible but given the variation in the scale of taxonomic identification among arthropod components, statistical and descriptive analysis was conducted at the order-level. Individual insects per sample were identified by using distinct insect characteristics such as antennae, paired fangs, a set of
wings, mandibles, or head capsules. All fecal sample sorting and identification was conducted by a single technician with unlabeled samples.

Fecal samples were separated into two categories: adult and nestlings, but combined across years and across sexes due to small samples sizes. Flycatcher diet was reconstructed by calculating the abundance, frequency and occurrence of the nine major prey types by flycatcher age group. Prey type frequency was quantified as the total number of items of prey type $X$ in sample $Y$ divided by the total number of prey items in sample $Y$. Occurrence was defined as the proportion of all fecal samples containing prey type $X$ (Rosenberg and Cooper 1990, Durst et al. 2008). Frequency measures proportional abundance of prey type $X$ while occurrence is a measure of the incidence of prey type $X$ across all fecal samples. In combination, frequency and occurrence provides a balanced measure of the diet composition of the sampled population during the sampling period (Durst et al. 2008).

We compared breeding season diet overlap across eight Willow Flycatcher diet studies including: Beal (1912; $n = 135$), Prescott and Middleton (1988, $n = 7+$), DeLay et al. (2002, $n = 23$), Drost et al. (2003, $n = 50$), Wiesenborn and Heydon (2007, $n = 56$), and Durst et al. (2008, $n = 341$). We quantified diet overlap among studies using Pianka’s index (Krebs 1994):

$$O_{jk} = \frac{\sum P_{ij}P_{ik}}{\sqrt{\sum P_{ij}^2 \sum P_{ik}^2}} \quad (1)$$

where $P_{ij}$ is the frequency of prey item $i$ at study site $j$ and $P_{ik}$ is the frequency of prey item $i$ at study site $k$. Pianka’s index measures the percent overlap in diet between sites $j$ and $k$ at the taxonomic level of order. Pianka’s index ranges from 0 to 1 with higher values indicating greater degrees of dietary overlap. We used the pgirmess package in program R (available at http://cran.r-project.org/) to estimate Pianka’s index.
RESULTS

Stable isotopes.-Over the 2003, 2004, and 2005 breeding seasons at Fish Creek, we collected feathers from 31 hatch year and 32 adult Willow Flycatchers. Carbon isotopes values varied more widely among feathers from male than female or hatch year flycatchers (Table 3.1, Fig. 3.1). δ\(^{13}\)C feather values were not found to be influenced by the interaction of year and flycatcher age (\(F_{2,61} = 1.32, P = .28\)). After applying a Tukey’s honest significant differences test, we identified significant differences in δ\(^{13}\)C signatures between adult and hatch year feathers (\(P < .0001\)). In contrast, δ\(^{13}\)C signatures did not differ between male and female flycatchers (\(P = .60\)). Hatch year flycatcher feathers, on average, were more \(^{13}\)C depleted than adult flycatcher feathers.

The feathers from hatch year flycatchers showed less variation in their δ\(^{15}\)N signatures than the feathers from male and female flycatchers, and on average the hatch year feathers were more depleted in \(^{15}\)N than the adult flycatcher feathers (Table 3.1, Fig. 3.1). No interaction effect was found between year and age in δ\(^{15}\)N signatures. Tukey multiple comparison tests indicated differences between male and hatch year δ\(^{15}\)N signatures (\(P < .001\)) but no differences in δ\(^{15}\)N values were detected between female and hatch year flycatchers.

δ\(^{13}\)C values ranged wider in aquatic insects than in terrestrial insects (Table 3.1, Fig. 3.1). The opposite was true of δ\(^{15}\)N values where greater variation was observed in terrestrial insects than aquatic insects. An interaction effect between year and prey type was found for δ\(^{13}\)C values (\(F_{2,135} = 3.91, P = .05\)) but not for δ\(^{15}\)N values. In further exploration, the interaction effect was due to a decrease in the aquatic insect’s mean δ\(^{13}\)C value from 2004 to 2005. However, the difference in mean aquatic insect δ\(^{13}\)C value between 2004 and 2005 was not found to be significant (\(t_{47} = -1.53, P = .14\)). A Tukey multiple comparison test found differences in δ\(^{13}\)C but not δ\(^{15}\)N values between aquatic and terrestrial insects (\(P < .001\) and \(P = .65\), respectively). The
mean $\delta^{13}$C value for aquatic insects was more depleted than the mean $\delta^{13}$C value for terrestrial insects.

Mean $\delta^{13}$C enrichment, the difference between the average isotope value of potential prey and the isotope values of the individual feathers, from aquatic insects ranged from 3.5 in nestling feathers to 6.7 in feathers from male flycatchers while mean $\delta^{13}$C enrichment from terrestrial insects ranged from 1.9 in nestling feathers to 5.1 in feathers from male flycatchers (Table 3.1). Mean change in $\delta^{15}$N from aquatic insects to feathers ranged from 2.1 in nestling feathers to 4.0 in male flycatchers while mean change in $\delta^{15}$N from terrestrial feathers ranged from 1.9 in nestling feathers to 3.8 in the feathers of male Willow flycatchers.

![Graph showing mean δ13C and δ15N values (±SD) for Willow Flycatcher feathers and potential prey items examined at Fish Creek, Utah, USA.](image)

Fig. 3.1. Mean $\delta^{13}$C and $\delta^{15}$N values (±SD) for Willow Flycatcher feathers and potential prey items examined at Fish Creek, Utah, USA.
Table 3.1. Mean δ¹³C, δ¹⁵N values, Δ¹³C and Δ¹⁵N enrichment values (±SD) for Willow Flycatcher and potential prey items.

<table>
<thead>
<tr>
<th>Sample</th>
<th>n</th>
<th>Mean ± SD</th>
<th>Range</th>
<th>Mean ± SD</th>
<th>Range</th>
<th>Δ¹³C Enrichment (‰)</th>
<th>Δ¹⁵N Enrichment (‰)</th>
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<th>Terrestrial</th>
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<tr>
<td>Male</td>
<td>15</td>
<td>-20.0 ± 2.7</td>
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<td>3.1 ± 0.6</td>
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Table 3.2. Pianka’s index estimates of diet overlap among 7 Willow Flycatcher studies.

<table>
<thead>
<tr>
<th></th>
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<th>Beal</th>
<th>Durst et al</th>
<th>Drost et al</th>
<th>Delay et al</th>
<th>Wiesenborn and Heydon</th>
<th>Prescott and Middleton</th>
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<tr>
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<td>0.572</td>
<td>0.896</td>
<td>0.639</td>
<td>1</td>
<td>0.882</td>
</tr>
<tr>
<td>Prescott and Middleton</td>
<td>0.144</td>
<td>0.403</td>
<td>0.389</td>
<td>0.650</td>
<td>0.318</td>
<td>0.882</td>
<td>1</td>
</tr>
</tbody>
</table>
Our Bayesian mixing models detected a greater consumption of terrestrial insects than aquatic insects by male, female and hatch year birds. Aquatic insects comprised 28% ±4.82 SD (posterior high density region = 0 to 67%), 22% ±3.73 SD (posterior high density region = 0 to 56%) and 13% ±1.13 SD (posterior high density region = 0 to 32%) of male, female, and hatch year Willow Flycatchers, respectively. Terrestrial insects comprised 72% ±4.82 SD (posterior high density region = 33% to 100%), 78% ± 3.73 SD (posterior high density region = 44% to 100%), and 87% ±1.13 SD (posterior high density region = 68% to 100%) of male, female, and hatch year Willow Flycatchers, respectively.

Fig. 3.2. Mean abundance (±SD) of nine prey groups for adult (n = 18) and nestling (n = 25) Willow Flycatchers at Fish Creek, Utah.

_Fecal sample analysis_- Fifty-seven fecal samples were collected over the 2003, 2004, and 2005 breeding seasons yielding a total of 150 identifiable prey items (Fig. 3.2). The fecal samples were comprised primarily of hymenoptera and coleoptera but seven other orders of
insects were represented in the samples. We identified approximately 75% of the fragments in the fecal samples. On average, coleoptera and hymenoptera frequency was higher in nestling than adult fecal samples however frequency differences of these prey items were not statistically significant (Fig. 3.3). Hymenoptera and coleoptera occurred in 80% and 60% of nestling fecal samples, respectively, and 61% and 56% of adult fecal samples, respectively (Fig. 3.4). Overall, the nestling fecal samples \((n = 8 \text{ insect orders})\) were more prey species rich than the adult fecal samples \((n = 5 \text{ insect orders})\).

Diet overlap among Willow Flycatcher studies ranged from 0.14 (current study and Prescott and Middleton 1988) to 0.95 (Beal 1912 vs. Delay et al. 2002, Table 3.2). The overall diet of Willow Flycatchers sampled in this study most closely resembled the diets sampled by Beal (1912) and DeLay et al. (2002). Diet overlap across all other studies varied from 0.318 in Prescott and Middleton (1988) and DeLay et al. (2002) to 0.955 in DeLay et al. (2002) and Beal (1912).

**DISCUSSION**

In this study, we investigated the contribution of aquatic insects to the flycatcher diet, examined differences in the diet consumed by adult flycatchers versus the diet adults feed to their nestlings, and compared the diet of Willow Flycatchers at Fish Creek with the diet of Willow Flycatchers reported in previously published studies. We derive three major points from our analysis. First, aquatic insects contribute to the Willow Flycatcher diet at Fish Creek in proportions similar to those found in other bird species. Second, we observed little variation in the diet of male and female adult flycatchers however adult Willow Flycatchers appear to consume a different diet than the one they feed to their nestlings. Third, the diet of Willow Flycatchers at Fish Creek is most similar to the diets described in Beal (1912) and DeLay et al. (2002). We base our conclusions on evidence from both stable isotope and fecal sample analyses.
Fig. 3.3. Mean diet frequency/sample (±SD) of nine prey groups for adult (n = 18) and nestling (n = 25) Willow Flycatchers at Fish Creek, Utah.

**Contribution of Aquatic insects.** Although terrestrial insects comprised large proportions of the diet of adult and hatch year Willow Flycatchers at Fish Creek during the 2004 and 2005 breeding seasons, aquatic arthropod subsidies comprised almost 1/3 of the diet of adult Willow Flycatchers and 13% of the diet of hatch year birds. These findings are consistent with results from previous studies investigating consumption of aquatic insects in a range of bird species (Nakano and Murakami 2001, Murakami and Nakano 2002). Nakano and Murakami (2001) showed that aquatic insects comprised 15.5% and 31.8% of the diets of two summer resident flycatcher species, the Brown Flycatcher and the Narcissus Flycatcher, at Horonai stream in Hokkaido, Japan.
Fig. 3.4. Occurrence of nine prey groups for adult (n = 18) and nestling (n = 25) Willow Flycatchers at Fish Creek, Utah.

Evidence from this study, as well as previous Willow Flycatcher diet studies, suggests that the use of aquatic insects by Willow Flycatchers may be influenced by the insect productivity in the riparian breeding habitats as well as the habitats adjacent to nesting habitat. Wiesenborn and Heydon (2007) found that flycatchers nesting in Tamarisk dominated habitats in Arizona relied heavily on Odonata derived from aquatic habitats and concluded that in Tamarisk dominated habitats with low in situ arthropod production, insect subsidies from adjacent habitats may be essential to the Willow Flycatcher during the breeding season. In contrast, DeLay et al. (2002) investigated variation in Willow Flycatcher diet in birds breeding in native riparian habitat in the Gila Valley, New Mexico, and found only evidence of low use of aquatic insects by flycatchers. This variation in the use of aquatic insect subsidies appears to reflect relative productivity of habitats surrounding the riparian zone. The potential arthropod productivity of flycatcher nesting habitat should be considered by land managers when identifying areas to
protect for flycatchers during the breeding season. Depending on the breeding location, habitats adjacent to riparian land cover may be an essential source of food resources to Willow Flycatchers during the breeding season.

Willow Flycatcher’s dependence on aquatic insects is likely to vary temporally across the breeding season. Peak benthic productivity in temperate creeks typically occurs during spring (Sumner and Fisher 1979), and correspondingly, aquatic insect availability may also peak during spring. Specific timing of aquatic insect emergence varies across species (Corbet 1964) and is influenced by local variation in nutrition and climate (Needham et al. 1935, Sweeney and Vannote 1982). Aquatic insect hatches can provide abundant but temporally limited and stochastic sources of food. This was observed at Roosevelt Lake where one breeding male Willow Flycatcher was radio-tracked moving approximately 2 kilometers from his home range to feed on a mayfly hatch on the Salt River (Cardinal and Paxton 2004).

Our mixing models measured Willow Flycatcher’s average use of aquatic and terrestrial at Fish Creek during body feather molt which typically occurs late in the breeding season. We did not capture Willow Flycatcher’s use of aquatic insects towards the beginning of the breeding season but suspect that it could be higher than the levels observed in this study due to the timing of peak aquatic arthropod emergence, variation in the insect productivity of terrestrial habitats, and the observation of high foraging of aquatic insects in the spring by other bird species in temperate systems (Smith et al. 1998, Nakano and Murakami 2001, Gende and Willson 2001).

*Diet differences in adult and nestling flycatchers.* Male and female Willow Flycatchers did not differ statistically in their δ^{13}C or δ^{15}N values and although the mixing models found that the diet of male flycatchers was comprised of a higher proportion of aquatic insects than the diet of female flycatchers, these differences were not statistically significant. These results corroborate findings from other Willow Flycatcher diet studies that have identified only subtle degrees of diet differences between male and female flycatchers (DeLay et al. 2002, Drost et al.
2003, Wiesenborn and Heydon 2007, Durst et al. 2008). We did observe considerable individual variation in stable isotope values among adult Willow Flycatchers likely reflecting individual differences in their foraging behavior. Stream geomorphology, riparian habitat heterogeneity and variation in benthic productivity are known to affect the flux of emerging aquatic insects (Iwata et al. 2003, Baxter et al. 2005). Individual variation in carbon and nitrogen stable isotope values among adult flycatchers may also reflect spatial variation in the availability of aquatic insects across home ranges.

Previous studies have consistently observed variation in the type and proportions of prey types consumed by adult Willow Flycatchers versus that fed to nestling flycatchers (Prescott and Middleton 1988, Drost et al. 2003, Wiesenborn and Heydon 2007, Durst et al. 2008). Our study indicates that diet differences between adults and nestlings are also present in their use of aquatic insects. A number of factors may explain the discrepancy between adult and nestling flycatchers in their consumption of aquatic insects. First, adult Willow Flycatchers may be selectively feeding nestlings different prey items than they select for themselves due to differences in dietary requirements for adults and nestling birds (Newton 1967). Adult flycatchers may be selecting prey items with higher nutrient content and, more specifically, predaceous insects which have been found to contain greater nitrogen content than herbaceous insects (Fagen et al. 2002). Herbaceous and predaceous insects from aquatic (e.g. aquatic Diptera versus Odonata) and terrestrial (e.g. pollen-feeding bees versus Camponotus sp.) habitats were identified in fecal samples of nestling flycatchers. However, we encountered a greater number of predaceous terrestrial insects than predaceous aquatic insects in the nestling’s fecal samples.

To examine if differences in nitrogen content exist between aquatic and terrestrial insects, we looked post-hoc at the mass spectrometry results which provide measurements of nitrogen concentration in the insect samples used in the stable isotope analysis. In our sample, a pattern began to emerge where terrestrial insects (mean = 0.12, SD = 0.002) contained higher
concentrations of nitrogen than aquatic insects (mean = 0.11, SD. = 0.003, \( P = .06, t_{46} = -1.94 \)).

We suspect that at Fish Creek a greater number of predaceous insects are produced in mountain shrub steppe and upland forest habitats than in aquatic habitats. Adult flycatchers may be intentionally selecting predaceous terrestrial insects to feed to their young. If this is the case, then this is the second piece of evidence we have identified that indicates that alternative habitats bordering riparian habitat including mountain shrub steppe and upland forest are important for providing food resources to Willow Flycatchers during the breeding season. Further study involving experimentation is required however to determine if adult flycatchers are preferentially selecting predaceous terrestrial arthropods to feed to their young at Fish Creek.

Alternatively, diet differences between nestling and adult Willow Flycatchers may be the result of temporal differences in feather sampling. Nestling feather development occurs largely in July at Fish Creek while adult body feather molt begins in August. Nestling and adult feather isotope signatures therefore reflect two distinct time periods at Fish Creek with potentially different arthropod availability.

We expected \( \delta^{15}N \) enrichment to follow a step-wise progression from prey source to consumer tissue within the range of 3-5‰ (Peterson and Fry 1987, Mizutani et al. 1992, Hobson and Bairlein 2003). This expectation was satisfied in the nitrogen enrichment of adult flycatcher feathers from terrestrial and aquatic arthropod prey however mean nitrogen enrichment levels were lower than we expected in nestling feathers. Hatch year feathers were found to be more depleted in \( ^{15}N \) than male but not female feathers. Since \( \delta^{15}N \) values indicate the trophic-level at which a consumer is foraging, we suggest four possible scenarios responsible for differences in \( ^{15}N \) between male and hatch year feathers. One, we may have missed sampling an insect food source consumed primarily by males that is more \( ^{15}N \) enriched on average than the insects we sampled. Conversely, we may have missed a food source commonly fed to nestlings that is more \( ^{15}N \) depleted than the food items we sampled. Differences in the feather structure itself between
hatch year and adult feathers may be responsible for differences in nitrogen enrichment between adult and nestling flycatcher feathers. Finally, as Willow Flycatcher’s body molt may occur any time from late July thru November, we may have unknowingly sampled body feathers grown during fall migration. Carbon and nitrogen isotope signatures would thus reflect the diet consumed by Willow Flycatchers while on migration rather than the Fish Creek diet.

*Using stable isotopes in bird diet analysis.* The precision of our aquatic and terrestrial insect estimates depends on the accuracy of the $\delta^{13}\text{C}$ discrimination factor used in our mixing models. The change in $\delta^{13}\text{C}$ from prey source to feather has been found to vary considerably across bird species and prey items (Mizutani et al. 1992, Hobson and Bairlein 2003). We used a $\delta^{13}\text{C}$ trophic discrimination factor of 2.0 ± 0.1 and based this choice on laboratory studies that were conducted with bird species and diets most similar to the Willow Flycatcher (Hobson and Bairlein 2003, Pearson et al. 2003). A more accurate determination of the $\delta^{13}\text{C}$ discrimination factor to use in our mixing models would require laboratory experiments of isotope fractionation in Willow Flycatchers fed a homogeneous insect diet. The benefit of using a Bayesian mixing model over traditional mixing models (e.g. Phillips and Gregg 2001, 2003) is its ability to incorporate some of the uncertainty in trophic enrichment factor into model parameter estimation. However, there remains a considerable need for additional laboratory experiments to provide precise diet-tissue discrimination factors for use in isotope mixing-models for ascertaining wild bird population diets (Gannes et al. 1997, Martinez del Río et al. 2009).

To further address the problem of $\delta^{13}\text{C}$ isotopic discrimination uncertainty, we conducted a post-hoc exploration of the influence of varying $\delta^{13}\text{C}$ discrimination factor on flycatcher diet composition by incrementally increasing the $\delta^{13}\text{C}$ discrimination factor by 0.5‰ starting at 1.0‰ and ending at 4.5‰. We found that the diet output from male and female mixing-models to behave robustly across the range of $\delta^{13}\text{C}$ isotopic discrimination values. For example, in the male flycatcher mixing-models, the mean proportion of their diet comprised of aquatic insects ranged
from 28% to 30% across the entire range of $\delta^{13}$C trophic enrichment values. Greater variation was observed in the proportion of aquatic and terrestrial insects comprising the hatch year flycatchers under varying $\delta^{13}$C trophic enrichment values. The mean contribution of aquatic insects to the hatch year diet was observed to increase with increasing $\delta^{13}$C trophic enrichment value so that their diet appeared to be dominated by aquatic insects when using trophic enrichment values at the extreme end of the range (4.5‰). Given these post-hoc findings, we feel confident in our choice of a 2.0‰ isotopic discrimination factor.

_Diet comparisons with other studies._ We examined diet overlap in Willow Flycatchers across seven flycatcher studies including six previously published diets as well as the diet reported in this study. In combination, the six previously published diet studies examined Willow Flycatcher diet in varying depths across much of their North American breeding range including parts of Canada. Four out of the six studies specifically investigated diet of the federally listed endangered Southwestern Willow Flycatcher during the breeding season at various sites in California, Arizona and New Mexico using fecal sample analyses (Delay et al. 2002, Drost et al. 2003, Wiesenborn and Heydon 2007, Durst et al. 2008). Beal (1912) collected stomach contents from 135 Willow Flycatchers in 17 states and three Canadian provinces from May to September. Given his sampling time frame, it is likely that some of his samples came from birds in migration and the diet samples from migrating birds do not reflect their diet during the breeding season adding a source of error to our investigation of diet overlap during the breeding season. Prescott and Middleton (1988) collected gut samples from seven adult Willow Flycatchers, and insect prey samples from an unspecified number of nestlings with neck ligatures in Guelph, Ontario. In contrast to other flycatcher diet studies, Prescott and Middleton (1988) treated individual diet prey items as the individual sample rather than the stomach or fecal sample.

There is considerable variation in diet overlap across Willow Flycatcher populations, and the pattern in dietary overlap cannot be entirely explained by geographic proximity. The diet of
the Fish Creek Willow Flycatchers most closely resembles the diet sampled by Beal (1912) and Delay et al. (2002). In Beal (1912), Willow Flycatcher diet was sampled from across their North American breeding range while DeLay et al. (2002) examined diet in a population of Southwestern Willow Flycatchers breeding in the Gila Valley, New Mexico. Willow Flycatcher’s high consumption of Hymenoptera and Coleoptera was the common trend across these three studies. Fish Creek Willow Flycatcher diet was most dissimilar from the diet of nestling Willow Flycatchers in southeastern Ontario. The diet of the Ontario population of nestling Willow Flycatchers was dominated by Diptera species, and although the authors did not quantify the diet of adult flycatchers in their study, they did observe differences in the diet of adult and nestling flycatchers. Part of the discrepancy between the Fish Creek and Ontario flycatcher diets may be due to differences in diets sampled; nestling flycatchers were the focus in the Ontario study while we examined diet in both adult and nestling flycatchers. Diptera species comprised a larger proportion of the diet of nestling flycatchers at Fish Creek than adult flycatchers although not at levels anywhere close to those observed in the Ontario population. The Ontario nestling population’s diet may be unique among the diets of the flycatcher populations studied while the flycatcher diet described by Beal (1912) was most congruent with other flycatcher diets. Beal’s (1912) Willow Flycatcher sample included a wide geographic range while the other flycatcher studies examined flycatcher diet in distinct populations. Beal (1912) appears to have captured the general diet of Willow Flycatchers across broad geographic scales while other studies have demonstrated the variability in Willow Flycatcher diets on finer geographic scales. Also, if Willow Flycatchers are generalist foragers (Durst et al. 2008), we may expect flycatcher diets to differ among sites due to differences in the distribution of arthropod populations, local and regional composition and structure of habitats, climate patterns, and random forces.
Conclusions and management implications. Willow Flycatcher diet at Fish Creek is largely comprised of terrestrial insects however aquatic insects make up 20%-30% of the diet of adult flycatchers. Similar to other studies, we found considerable differences in the diets consumed by adults compared to the diet they feed their nestlings. Further, many of the insects identified in fecal samples were likely produced in non-riparian habitats, either aquatic or upland terrestrial habitats. The use of insect subsidies derived from neighboring habitats by Willow Flycatchers suggests that the availability of adjacent habitat types may be important for producing food resources to complement in situ riparian arthropod production. As conservation and management plans are focused on preserving or restoring habitat for the Willow Flycatcher, in addition to preserving riparian habitat for breeding, wildlife managers need to consider the movement of insect prey across habitat boundaries. If low insect productivity in riparian habitat is suspected, adjacent habitats should be preserved to provide the food resources required by Willow Flycatchers during the breeding season.

LITERATURE CITED


CHAPTER 4
SPACE USE COMPARISONS IN TWO POPULATIONS OF WILLOW FLYCATCHER, EMPIDONAX TRAILII¹

Abstract. The Willow Flycatcher, Empidonax traillii, has experienced population declines throughout its range in the western United States with one subspecies Empidonax traillii extimus listed as an endangered species. Consequently, most of the research on Willow Flycatchers has been focused on the federally endangered Southwestern Willow Flycatcher, E.t. extimus. In this study, we compare and contrast space use characteristics in two populations of Willow Flycatchers, one belonging to the E.t. extimus subspecies and the other belonging to the E.t. adastus subspecies as a function of breeding site, breeding status, and sex. Willow Flycatchers were radio-tagged and tracked over the course of two breeding seasons at Fish Creek (2003, 2004, E.t. adastus) and three breeding seasons at Roosevelt Lake (2003-2005, E.t. extimus). Differences in home range size, core area size, proportion of core area comprised of riparian habitat, home range habitat richness and home range heterogeneity were found among breeding-flycatchers as a function of breeding site and sex. Variation in space use characteristics as a function of breeding site, breeding status, and sex indicates that a number of different mechanisms may be driving space use in Willow Flycatchers over the breeding season.

INTRODUCTION

Knowledge of an animal’s use of space is vital for effective conservation and management planning. Currently, avian population managers in need of demographic and habitat requirement information for the active management of Willow Flycatcher populations rely on research studies conducted on the endangered E. t. extimus subspecies. In this study, we compare home range and core area space use in two populations of Willow Flycatchers, an E.t.

¹ Coauthored by Bakian, A.V., K.A. Sullivan, and E.H. Paxton
extimus population breeding at Roosevelt Lake, Arizona and a population of E.t. adastus breeding at Fish Creek, Utah to examine the generality of the studies of space use in one population for managing other populations.

The Willow Flycatcher (Empidonax traillii) is a small, neo-tropical migrant that depends upon riparian habitat for survival and reproduction throughout the continental United States (Fig. 1.1). The Southwestern Willow Flycatcher (Empidonax traillii extimus; SWFL) is a federally endangered subspecies with a breeding distribution spanning six states including Arizona, New Mexico, southern Colorado, southern Utah, Nevada and Southern California (U.S. Fish and Wildlife Service 2002). Population declines in the Southwestern Willow Flycatcher are primarily the result of wide-spread habitat loss, degradation or modification (U.S. Fish and Wildlife Service 1993, Marshall and Stoleson 2000). Since receiving federal endangered species protection in 1995 (U.S. Fish and Wildlife Service 1995), SWFLs have been the subject of detailed population surveys, monitoring and demographic study (e.g. Paxton et al. 1997, English et al. 1999, Kenwood and Paxton 2001, Newell et al. 2003, Causey et al. 2005, Paxton et al. 2007).

The Empidonax trailli adastus (WIFL) subspecies of Willow Flycatcher breeds throughout the intermountain west and Great Basin region of the U.S including Utah, Colorado, Wyoming, Idaho, Nevada, eastern California, eastern Oregon and eastern Washington. Similar to the SWFL, this sub-species of flycatcher restricts its breeding to riparian woodlands that typically occur in isolated patches. Populations of E.t. adastus are also in decline (Schlorff 1990, Sauer et al. 1997, Stefani et al. 2001) yet it has received considerably less research attention.

We used ratio-telemetry to track female and male flycatchers at Fish Creek and male flycatchers at Roosevelt Lake during the breeding season. Previous estimates of Willow Flycatcher space use (e.g. home range, territory, or core area) have relied primarily on mapping the movement of individual’s within the landscape based on visual and auditory identification (Walkinshaw 1966, Eckhardt 1979, Stafford and Valentine 1985, Flett and Sanders 1987, Prescott
Territorial mapping techniques have been found to underestimate the true space requirements in some passerines (Hanski and Haila 1988, Anich et al. 2009). In addition, as singing is uncommon in female Willow Flycatchers (Sedgwick 2000), radio-telemetry may more accurately capture space use than territory mapping in females as well as males.

The mechanisms responsible for intraspecific variation in home range size are poorly understood (Kjellander et al. 2004, Saïd and Servanty 2005). Potential variables that may influence home range size variation within a species include sex and age (Cederlund and Sand 1994), reproductive status (Bertrand et al. 1996), population density (Kjellander et al. 2004) and landscape heterogeneity (Kie et al. 2002). Landscape structure and composition can influence home range and core area size by impacting the distribution of food resources (Smith and Shugart 1987), the availability of shelter (Fisher 2000) and the presence of predators (reviewed in Whittingham and Evans 2004). The patch and landscape level vegetation structure of Willow Flycatcher habitats differ between Roosevelt Lake and Fish Creek. At Roosevelt Lake, temporal fluctuations in reservoir water levels due to the operation of Roosevelt Dam have produced a mosaic of riparian woodland stands with varying vegetation age and canopy heights (Paxton et al. 2007). Riparian woodland stands are embedded in a xeric landscape comprised of open areas and Sonoran desert scrub habitat. In contrast, Fish Creek has patches of fairly uniform riparian willow stands situated in a broad canyon bordered by upland forest and mountain shrub habitats (Bakian unpublished data). We predict that differences in flycatcher home range and core area size are influenced by variation in the habitat vegetation structure and pattern at Fish Creek and Roosevelt Lake. In addition, we expect space use metrics to vary as a function of flycatcher sex due to behavioral differences between male and female flycatchers. Our study’s primary objective is to compare and contrast space use in Willow Flycatchers including home range and core area size, home range and core area habitat heterogeneity and habitat composition as a function of breeding site, and breeding status and flycatcher sex.
METHODS

STUDY AREA

Two geographically disparate populations of Willow Flycatchers were examined in this study. The first is a population of *Empidonax traillii adastus* breeding at Fish Creek, a perennial, high elevation stream in Manti-La Sal National Forest, Utah (Fig. 4.1). The second group is a population of the federally endangered Southwestern Willow Flycatcher, *Empidonax traillii extimus*, breeding along the Salt River and Tonto Creek inflows of Roosevelt Lake, Gila County, Arizona (Fig. 4.2).
Breeding habitat differed by both vegetation composition and riparian patch size between the two study sites. The Fish Creek drainage is composed of linear patches of thick, willow dominated (*Salix* spp.) riparian habitat with a maximum canopy height of 5 meters. These distinct riparian patches range from 0.29 ha to 2.5 ha and are bordered by mountain shrub steppe habitat on southern slopes characterized by big sagebrush (*Artemisia tridentate* sp.), Utah serviceberry (*Amelanchier utahensis*), chokecherry (*Prunus virginiana*), mountain snowberry (*Symphoricarpos oreophilus*) and various shrubsteppe grasses. Riparian habitat is bordered by upland mixed-forest habitat with Englemann’s spruce (*Picea engelmannii*), White fir (*Abies concolor*) Douglas fir (*Pseudotsuga menziesii*) forest, and Quaking aspen (*Populus tremuloides*)
species on north-facing canyon slopes. Riparian patches are separated by open water. Each
distinct patch of riparian habitat typically contained a single pair of breeding flycatchers during
the study period (Bakian personal observation).

The Roosevelt Lake study site is a low elevation (~690 m) desert riparian zone comprised
of patches of riparian habitat ranging from 0.2 ha to 43 ha which are separated by bare ground,
scrub habitat, emergent riparian habitat or open water. Mature riparian habitat patches are
composed of Gooding’s willow (Salix gooddingii), exotic saltcedar (Tamarix ramosissima) or a
combination of the two. Sonoran desert uplands surround flycatcher breeding habitat and consist
of palo verde (Cercidium microphyllum), creosote (Larrea tridentate), saguaro cacti (Carnegiea
gigantea), and screwbean mesquite (Prosopsis pubescens) (see Paxton et al. 2007, Cardinal 2005
for more detail). In contrast to Fish Creek, riparian habitat patches at Roosevelt Lake often
support more than one pair of nesting Willow Flycatchers.

CAPTURE AND TRANSMITTER ATTACHMENT

Data was collected over the 2003 and 2004 breeding seasons at Fish Creek and over the
2003, 2004 and 2005 breeding seasons at Roosevelt Lake. Willow Flycatchers typically arrive at
Fish Creek in late May and at Roosevelt Lake in early May. Following arrival and territory
establishment, Willow Flycatchers were selected for capture and radio transmitter attachment by
assigning a number to each territory and drawing a number at random. Both male and female
flycatchers were studied at Fish Creek while only male flycatchers were sampled at Roosevelt
Lake due to the endangered status of the subspecies. Sex was determined based on behavior, the
presence of a brood patch and lack of a cloacal protuberance in females, and the presence of a
cloacal protuberance and lack of a brood patch in males. Occasionally wing chord and tail length
was used to aid in determining sex (Table 3 in Pyle 1997, USGS unpublished data). At Roosevelt
Lake, the sex of some flycatchers had been previously identified using sex-specific genetic
markers (Cardinal 2005).
Willow Flycatchers were captured using both passive and target mist-netting techniques (Sogge et al. 2001). Following capture, birds were individually banded with an individually numbered, color-anodized Federal bird band on one leg, and a colored metal band on the other leg (Koronkiewicz et al. 2005). We used the Holohil (Carp, Ontario) LB-2N (Utah and Arizona) or BD-2N (Arizona only) radio transmitters (21 day expected battery life; weight range 0.40-0.48 g). A lightweight grid-cloth was glued to the back of the transmitter to create a more textured surface area prior to attachment. Following capture, an area of feathers was removed on the lower back of the bird approximately 1.5cm above the uropygial gland. Transmitters were attached using a glue-on method (Johnson et al. 1992, Paxton et al. 2003) with Skin-bond® medical adhesive (Smith and Nephew®). The final weight of the transmitters including medical adhesive and grid-cloth was 0.46-0.50 g (approximately 3.8%-4.2% of the flycatcher’s weight). Flycatchers were released following 5 minutes of adhesive drying time, and the entire banding and transmitter application process took less than 20 minutes.

RADIO-TRACKING

Radio-tracking was started the day following transmitter attachment to provide time for the birds to acclimate to the presence of the transmitter (Suedkamp Wells et al. 2003). Each flycatcher was radio-tracked at least four times a day within at least 2 out of 4 pre-established time periods: AM early (0600-0915), AM late (0916-1230), PM early (1231-1545) and PM late (1546-1900). Individual tracking sessions were separated by at least 30 minutes to guarantee biological independence (White and Garrot 1990) of sequential tracking locations with the goal of collecting at least 30 locations per bird. Tracking equipment used included R-1000 Telemetry receivers (Communications Specialists, Inc.), and standard hand-held 3-element yagi antennas (Biotrack Equipment).

Flycatchers were located using the homing-in method (Paxton et al. 2003), and exact location was pin-pointed through visual confirmation or estimated through triangulation. The
bird’s geographical point location and position error was recorded in Universal Transverse Mercator coordinates via a handheld Global Positioning System (Garmin Etrex Legend) after the flycatcher moved from its pin-pointed location. Information recorded at point location included the bird’s behavior, habitat type, vegetation substrate, height position of the flycatcher in the vegetation, observation of foraging event, and vocalization type if heard. Radio-tracking was conducted for the lifetime of the transmitter battery or until the flycatcher became undetectable for other reasons.

Willow Flycatchers were categorized as “breeding” if they maintained and defended a territory, exhibited pair-mating behavior, and attempted/succeeded in nesting. Flycatchers were categorized as non-breeding if they were territorial and mate-paired but radio-tracked pre or post-breeding season, if they were territorial but not mate-paired, or if they exhibited “floater” behavior in which flycatchers were present but did not actively defend a territory (Sherry and Holmes 1989, Newton 1992).

DATA ANALYSIS

*Home range and core area estimation.* Home range is defined as an area that an organism normally uses to forage, breed and care for young (Burt 1943). We used the 95% fixed-kernel utilization distribution (UD) with least squares cross validation for estimating individual flycatcher home ranges. The 95% fixed-kernel UD corresponds to the area of landscape encompassing the 95% probability distribution for individual flycatchers. Kernel UD approaches are considered among the more rigorous home range quantification approaches (Kernohan et al. 2001). Fixed-kernel methods have been found to produce unbiased estimates of home range size when at least 30 telemetry locations are available for estimation (Seaman et al. 1999). We restricted our home range analysis to flycatchers with at least 28 radio locations. Home ranges were estimated in ArcView 3.3 using the ANIMAL MOVEMENT extension (Hooge and Eichenlaub 1997).
Core areas are areas within the home range that receive intensive use (Kernohan et al. 2001). Often, the 50% fixed kernel UD is used to represent home range core areas (Laver and Kelly 2008). The application of the 50% fixed kernel UD to identify core areas is arbitrary and lacking in biological support for many species. We used a core area estimation method described by Seaman et al. (1998) that determines core area probability isopleth size based on identifying the maximum isopleth containing a greater than expected density rule.

*Habitat composition.* We identified the habitat composition of home ranges and core areas from high resolution, rectified, aerial photographs of Fish Creek and Roosevelt Lake. The habitat types present at Fish Creek included mature riparian habitat (riparian vegetation > 1 meter height), young riparian habitat (riparian vegetation <1 meter height), mountain shrub steppe, upland forest, or other (bare ground and open water). Roosevelt lake habitat types included mature riparian habitat (riparian vegetation > 5 years old), young/emergent riparian habitat (riparian habitat < 5 years old), upland habitat (Sonoran desert upland vegetation), scrub (tamarisk dominated patchy vegetation), and other (bare ground and open water). At both Roosevelt Lake and Fish Creek, Willow Flycatchers select mature riparian habitat for nest site placement (Paxton et al. 2007, Bakian personal observation). Vegetation classification as determined by aerial photograph was validated through field checks.

We measured a number of home range and core area metrics for each Willow Flycatcher including home range size (in hectares), core area size (in hectares), the proportion of the home range comprised of mature riparian habitat, the proportion of the core area comprised of mature riparian habitat, home range habitat heterogeneity, core area habitat heterogeneity, home range habitat richness, and core area habitat richness. Habitat richness was measured as the number of habitat types present in each individual flycatcher’s home range and core areas. Shannon’s diversity index was used to estimate home range and core area heterogeneity ($H$),
\[ H = \frac{-\sum_{i=1}^{S} p_i \ln p_i}{\ln S} \]  

where \( S \) = habitat richness, and \( p_i \) = proportion of home range or core area comprised of habitat type \( i \).

Statistical analysis. One-way Analysis of Variance (ANOVA) was used to test for differences among Fish Creek female flycatchers, Fish Creek male flycatchers, and Roosevelt Lake male flycatchers in core UD isopleth size, home range size, core area size, home range and core area habitat composition (proportion comprised of riparian habitat), home range and core area habitat richness, and core area and home range habitat heterogeneity. The Student-Newman-Keuls (SNK) test and two-tailed t-tests assuming unequal variances were used for multiple-comparison testing following statistically significant overall ANOVA tests. Two-tailed t-tests assuming unequal variances was also used to test for differences in space use characteristics among breeding and non-breeding SWFLs at Roosevelt Lake. Separate ANOVAs were used to test differences among all Willow Flycatchers, breeding Willow Flycatchers and non-breeding Willow Flycatchers. To meet the assumption of normality, home range and core area size was natural log transformed prior to statistical analysis.

Separate linear regression models were fit to predict home range and core area sizes (natural log transformed) based on home range and core area metrics. Maximal home range and core area models included the following variables (with model variable name and type in parentheses): flycatcher sex (SEX, dummy variable), breeding status (BREED, dummy variable), population site (SITE, dummy variable), proportion of home range (HRRIP, continuous variable) or core area (CORIP, continuous variable) comprised of mature riparian habitat, and home range (HRHETERO, continuous variable) or core area heterogeneity (COHETERO, continuous variable). Models were evaluated with Akaike’s information criteria for small sample sizes (\( \text{AIC}_c \); Burnham and Anderson 2002). \( \text{AIC}_c \) weights were computed by standardizing \( \text{AIC}_c \).
values across models to sum to 1.0 which provides a measure of each individual model’s likelihood among all models in the model set (Burnham and Anderson 2002). Statistical analysis and modeling were conducted using SAS software, version 9.2 (SAS Institute 2008), and an alpha=0.05 was assumed for all statistical tests.

RESULTS

RADIO-TELEMETRY

In 2003, 2004, and 2005, a total of 93 Willow Flycatchers were radio tagged and tracked at Fish Creek and Roosevelt Lake. At Fish Creek, 13 females, 14 males and 8 flycatchers of unknown sex were tracked and 1371 total radio locations were collected. The number of radio locations ranged from 5-95/flycatcher with an average of 39.5 locations/bird. At least 28 radio locations were collected in 24 Willow Flycatchers (female n = 12, male n = 12) at Fish Creek. Of the Willow Flycatchers with sufficient radio telemetry locations to estimate home range, 18 were categorized as breeding and 6 were categorized as non-breeding (Table 4.1). Fifty-eight male Willow Flycatchers were radio-tracked at Roosevelt Lake from 2003-2005 and 1827 total radio locations were collected. The number of radio locations among the Roosevelt Lake flycatchers ranged from 3-71 points with an average of 33 locations/bird. Sufficient radio locations for conducting analysis were collected on 31 male flycatchers out of which 18 were categorized as breeding and 13 were categorized as non-breeding.

SPACE USE

Differences between flycatcher populations in space use were found primarily among breeding Willow Flycatchers (Table 4.1). Male breeding flycatcher’s mean core area size at Fish Creek was significantly larger than the mean size of female Fish Creek flycatcher’s core areas (t_{5.245} = -4.12, P = <.001) and Roosevelt Lake male flycatcher’s core areas (t_{14.262} = 3.58, P = .003; Table 4.1). Similarly, mean home range size was significantly larger for male flycatchers at
Fish Creek than for female flycatchers at Fish Creek ($t_{12.374} = -3.32, P = .006$) and male flycatchers at Roosevelt Lake ($t_{17.311} = 4.67, P < .001$, Table 4.1). Among breeding birds, female flycatchers at Fish Creek had a greater proportion of riparian habitat in their core areas than male flycatchers at Fish Creek ($t_{9.75} = -2.17, P = .01$) or Roosevelt Lake ($t_{17.27} = 3.92, P < .01$). Differences in the proportion of riparian habitat in their core areas did not differ between Fish Creek males and Roosevelt Lake males ($t_{22.52} = 1.63, P = .12$). The mean home range heterogeneity in the home ranges of male flycatchers at Fish Creek was significantly greater than the mean home range heterogeneity in the home ranges of Fish Creek female ($t_{15.037} = -2.48, P = .03$) and Roosevelt lake male ($t_{12.677} = 2.38, P = .03$) flycatchers. Finally, among breeding flycatchers, Fish Creek male flycatcher home ranges had higher mean habitat richness than the home ranges of Roosevelt Lake male flycatchers ($t_{15.181} = 2.49, P = .03$). No differences were found in core area isopleth size, proportion of riparian habitat comprising the home range, core area habitat richness, or core area habitat heterogeneity among breeding flycatchers as a function of site or sex.

In the comparisons across all Willow Flycatchers regardless of breeding status, only mean home range habitat heterogeneity differed significantly by population. Fish Creek male flycatcher home ranges were significantly more heterogeneous than the home ranges of male Roosevelt Lake flycatchers ($t_{20.983} = 2.63, P = .02$; Table 4.1). Among the non-breeding flycatchers, core isopleth size, core area size, home range size, proportion of riparian habitat in core areas, proportion of riparian habitat in home ranges, core area habitat richness, home range habitat richness, core area heterogeneity and home range heterogeneity were not found to differ significantly as a function of flycatcher site or sex (Table 4.1).

The Seamen et al. (1998) rule was used to identify core areas in each home range. The kernel UD isopleth selected to represent core area did not vary statistically as a function of breeding site. Figure 4.3 displays the total number of times that each probability isopleth was
selected to represent the core area boundary. The average kernel UD size selected was 35% in
the Fish Creek female flycatcher population, 40% in the Fish Creek male flycatcher population
and 38.71% in the Roosevelt Lake male flycatcher population (Table 4.1).

![Histogram of core area isopleth counts for Willow Flycatchers](image)

**FIGURE 4.3.** Counts of the kernel UD isopleth selected to represent the core area boundary
using the Seaman et al. 1998 rule for each Willow Flycatcher by breeding site and sex: Fish Creek
females (pink), Fish Creek males (green), and Roosevelt Lake males (blue).

When differences in space use were examined as a function of breeding status at
Roosevelt Lake, some space use metrics were found to differ between breeding and non-breeding
flycatchers (Table 4.2). Small sample sizes of non-breeding flycatchers as a function of sex at
Fish Creek precluded us from conducting an analysis of breeding versus non-breeding Fish Creek
flycatchers ($n$ non-breeding male flycatchers = 3, $n$ non-breeding female flycatchers = 3, Table
4.1). Average core area isopleth size was larger in breeding than non-breeding flycatchers ($t_{28.86} = -2.19, P = .04$). Non-breeding flycatchers maintained larger mean core areas ($t_{14.32} = 2.88, P = .01$) and mean home range sizes ($t_{13.88} = 2.88, P = .01$) than breeding flycatchers. Other space use characters were not found to differ between breeding and non-breeding flycatchers at Roosevelt Lake (Table 4.2).

**PREDICTING HOME RANGE AND CORE AREA SIZE**

Eighteen models (nine home range and nine core area specific models) were fit to explore the relationship between home range and core area size and home range metrics and population attributes (Table 4.3). The home range model with the highest AICc weight (0.35) included breeding status and home range heterogeneity to predict home range size. The second most likely model ($w_I = 0.17$) included the effect of sex in addition to breeding status and home range heterogeneity to predict home range size. Breeding status was negatively associated with home range size while increasing home range heterogeneity was positively associated with home range size (Table 4.4). Figure 4.4 illustrates the strong linear relationship between home range habitat heterogeneity and home range size and that this pattern appears independent of population.

The core area model with the highest AICc weight (0.35) included sex, breeding status, and core area heterogeneity. The second most likely model ($w_I = 0.23$) included the effect of site in addition to sex, breeding status and core area heterogeneity on predicting core area size (Table 4.4). Both the breeding categorization and female sex were found to have a negative effect on core area size while core area heterogeneity and core area size were positively associated (Table 4.4). Figure 4.5 illustrates the strong linear relationship between core area habitat heterogeneity and core area size as a function of breeding site.
TABLE 4.1. Sample size (N), mean, and standard error (SE) of home range and core area metrics for Fish Creek female Willow Flycatchers, Fish Creek male Willow Flycatchers, and Roosevelt Lake male Willow Flycatchers further stratified by breeding status with F-statistic and P-value from one-way ANOVA analysis.

<table>
<thead>
<tr>
<th>Metric</th>
<th>All Willow Flycatchers</th>
<th>Fish Creek Females</th>
<th>Fish Creek Males</th>
<th>Roosevelt Lake Males</th>
<th>F</th>
<th>df</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core isopleth</td>
<td>12</td>
<td>12</td>
<td>31</td>
<td>31</td>
<td>2,52</td>
<td>.51</td>
<td></td>
</tr>
<tr>
<td>Core area size(^a) (ha)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>2,33</td>
<td>.97</td>
<td></td>
</tr>
<tr>
<td>Home range size(^a) (ha)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>2,16</td>
<td>.99</td>
<td></td>
</tr>
<tr>
<td>Proportion core area riparian(^b)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>2,15</td>
<td>.85</td>
<td></td>
</tr>
<tr>
<td>Proportion home range riparian(^c)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>2,15</td>
<td>.85</td>
<td></td>
</tr>
<tr>
<td>Core area habitat richness</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>2,15</td>
<td>.85</td>
<td></td>
</tr>
<tr>
<td>Home range habitat richness</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>2,15</td>
<td>.85</td>
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</tr>
<tr>
<td>Core area habitat heterogeneity</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>2,15</td>
<td>.85</td>
<td></td>
</tr>
<tr>
<td>Home range habitat heterogeneity</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>2,15</td>
<td>.85</td>
<td></td>
</tr>
</tbody>
</table>

Breeding Willow Flycatchers

<table>
<thead>
<tr>
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<th>Fish Creek Females</th>
<th>Fish Creek Males</th>
<th>Roosevelt Lake Males</th>
<th>F</th>
<th>df</th>
<th>P</th>
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</thead>
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<tr>
<td>Core isopleth</td>
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<td>9</td>
<td>18</td>
<td>18</td>
<td>2.16</td>
<td>2.33</td>
<td>.13</td>
</tr>
<tr>
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<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>11.14</td>
<td>2.33</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Home range size(^a) (ha)</td>
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<td>9</td>
<td>9</td>
<td>9</td>
<td>9.01</td>
<td>2.33</td>
<td>&lt;.01</td>
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<tr>
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<td>9</td>
<td>9</td>
<td>9</td>
<td>5.13</td>
<td>2.31</td>
<td>.01</td>
</tr>
<tr>
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<td>9</td>
<td>9</td>
<td>9</td>
<td>2.68</td>
<td>2.31</td>
<td>.08</td>
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<tr>
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<td>9</td>
<td>9</td>
<td>9</td>
<td>2.31</td>
<td>2.31</td>
<td>.16</td>
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<tr>
<td>Home range habitat richness</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>2.31</td>
<td>2.31</td>
<td>.08</td>
</tr>
<tr>
<td>Core area habitat heterogeneity</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>2.31</td>
<td>2.31</td>
<td>.08</td>
</tr>
<tr>
<td>Home range habitat heterogeneity</td>
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<td>9</td>
<td>9</td>
<td>9</td>
<td>2.31</td>
<td>2.31</td>
<td>.08</td>
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</table>

Non-breeding Willow Flycatchers

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<th>Fish Creek Males</th>
<th>Roosevelt Lake Males</th>
<th>F</th>
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<td>3</td>
<td>13</td>
<td>13</td>
<td>2.16</td>
<td>2.16</td>
<td>.20</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>2.16</td>
<td>2.16</td>
<td>.97</td>
</tr>
<tr>
<td>Home range size(^a) (ha)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2.16</td>
<td>2.16</td>
<td>.97</td>
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<tr>
<td>Proportion core area riparian(^b)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2.16</td>
<td>2.16</td>
<td>.85</td>
</tr>
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</table>
Proportion home range riparian\(^b\) & 3 & 0.74 & 0.10 & 3 & 0.84 & 0.05 & 11 & 0.39 & 0.08 & 1.24 & 2.14 & .32  
Core area habitat richness & 3 & 3.67 & 0.33 & 3 & 3.33 & 0.67 & 12 & 2.25 & 0.43 & 1.74 & 2.15 & .21  
Home range habitat richness & 3 & 4.67 & 0.33 & 3 & 4.67 & 0.33 & 11 & 3.73 & 0.38 & 1.37 & 2.14 & .29  
Core area habitat heterogeneity & 3 & 0.65 & 0.12 & 3 & 0.60 & 0.21 & 12 & 0.26 & 0.10 & 2.58 & 2.15 & .11  
Home range habitat heterogeneity & 3 & 0.81 & 0.09 & 3 & 0.79 & 0.01 & 11 & 0.58 & 0.08 & 2.01 & 2.14 & .17

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<th>Metric</th>
<th>(n)</th>
<th>Mean</th>
<th>SE</th>
<th>Breed</th>
<th>Non-breed</th>
<th>Breed</th>
<th>Non-breed</th>
<th>Breed</th>
<th>Non-breed</th>
<th>(t)</th>
<th>df</th>
<th>(P)</th>
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<td>13</td>
<td>41.67</td>
<td>34.62</td>
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<td>.04</td>
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<td></td>
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<tr>
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<td>0.04</td>
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<td>2.88</td>
<td>14.32</td>
<td>.01</td>
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</tr>
<tr>
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<td>0.51</td>
<td>0.58</td>
<td>0.11</td>
<td>0.12</td>
<td>0.42</td>
<td>24.52</td>
<td>.68</td>
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<td></td>
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<tr>
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<td>0.61</td>
<td>0.09</td>
<td>0.08</td>
<td>0.38</td>
<td>24.71</td>
<td>.70</td>
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<td>1.94</td>
<td>2.25</td>
<td>0.11</td>
<td>0.43</td>
<td>0.71</td>
<td>12.47</td>
<td>.49</td>
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<td></td>
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<td>Home range habitat richness</td>
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<td>11</td>
<td>3</td>
<td>3.73</td>
<td>0.22</td>
<td>0.38</td>
<td>1.64</td>
<td>16.67</td>
<td>.12</td>
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<td></td>
<td></td>
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<tr>
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<td>0.25</td>
<td>0.26</td>
<td>0.04</td>
<td>0.10</td>
<td>0.10</td>
<td>14.59</td>
<td>.92</td>
<td></td>
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<tr>
<td>Home range habitat heterogeneity</td>
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<td>0.44</td>
<td>0.58</td>
<td>0.05</td>
<td>0.08</td>
<td>1.54</td>
<td>16.66</td>
<td>.14</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Natural log transformed for analysis, non-tranformed values reported for mean and S.E.
\(^b\)Proportion of core area comprised of riparian habitat.
\(^c\)Proportion of home range comprised of riparian habitat.

TABLE 4.2. Sample size (\(N\)), mean and standard error (SE) of home range and core area metrics for breeding (breed) and non-breeding (non-breed) Willow Flycatchers at Roosevelt Lake with \(t\) statistic, degrees of freedom (df), and \(P\)-value from two-tailed \(t\)-tests assuming unequal variances.
TABLE 4.3. Candidate models predicting core area and home range size. Models with the lowest AICc and highest weights $w_i$ are best supported.

<table>
<thead>
<tr>
<th>Model</th>
<th>K</th>
<th>AICc</th>
<th>ΔAICc</th>
<th>$w_i$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Home range</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BREED + HRHETERO</td>
<td>3</td>
<td>36.59</td>
<td>0</td>
<td>0.35</td>
<td>0.42</td>
</tr>
<tr>
<td>SEX + BREED + HRHETERO</td>
<td>4</td>
<td>38.05</td>
<td>1.46</td>
<td>0.17</td>
<td>0.42</td>
</tr>
<tr>
<td>SITE + BREED + HRHETERO</td>
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<td>38.31</td>
<td>1.72</td>
<td>0.15</td>
<td>0.42</td>
</tr>
<tr>
<td>SEX + BREED + SITE + HRHETERO</td>
<td>5</td>
<td>38.37</td>
<td>1.78</td>
<td>0.14</td>
<td>0.44</td>
</tr>
<tr>
<td>HRHETERO</td>
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<td>38.77</td>
<td>2.18</td>
<td>0.12</td>
<td>0.37</td>
</tr>
<tr>
<td>SEX + BREED + SITE + HRHETERO + HRRIP</td>
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<td>39.57</td>
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<td>0.45</td>
</tr>
<tr>
<td>HRRIP</td>
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<td>&lt;0.001</td>
<td>0.17</td>
</tr>
<tr>
<td>BREED</td>
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<td>30.96</td>
<td>&lt;0.001</td>
<td>0.24</td>
</tr>
<tr>
<td>Intercept</td>
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<td>80.30</td>
<td>43.71</td>
<td>&lt;0.001</td>
<td>0</td>
</tr>
<tr>
<td><strong>Core area</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEX + BREED + COHETERO</td>
<td>4</td>
<td>28.67</td>
<td>0</td>
<td>0.36</td>
<td>0.63</td>
</tr>
<tr>
<td>SEX + BREED + SITE + COHETERO</td>
<td>5</td>
<td>29.51</td>
<td>0.84</td>
<td>0.23</td>
<td>0.64</td>
</tr>
<tr>
<td>BREED + COHETERO</td>
<td>3</td>
<td>29.61</td>
<td>0.94</td>
<td>0.22</td>
<td>0.61</td>
</tr>
<tr>
<td>SEX + BREED + SITE + COHETERO + CORIP</td>
<td>6</td>
<td>31.24</td>
<td>2.57</td>
<td>0.10</td>
<td>0.64</td>
</tr>
<tr>
<td>SITE + BREED + COHETERO</td>
<td>4</td>
<td>31.57</td>
<td>2.90</td>
<td>0.08</td>
<td>0.61</td>
</tr>
<tr>
<td>COHETERO</td>
<td>2</td>
<td>38.35</td>
<td>9.68</td>
<td>&lt;0.001</td>
<td>0.52</td>
</tr>
<tr>
<td>BREED</td>
<td>2</td>
<td>69.82</td>
<td>41.15</td>
<td>&lt;0.001</td>
<td>0.25</td>
</tr>
<tr>
<td>CORIP</td>
<td>2</td>
<td>70.71</td>
<td>42.04</td>
<td>&lt;0.001</td>
<td>0.11</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
<td>83.44</td>
<td>54.77</td>
<td>&lt;0.001</td>
<td>0</td>
</tr>
</tbody>
</table>

$^a$Number of model parameters.

TABLE 4.4. Coefficient estimates (β) and standard errors (S.E.) for best fit home range size and core area size regression models.

<table>
<thead>
<tr>
<th>Variable</th>
<th>β</th>
<th>S.E.</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Home range</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BREED</td>
<td>-0.89</td>
<td>0.44</td>
<td>.05</td>
</tr>
<tr>
<td>HRHETERO</td>
<td>3.91</td>
<td>0.87</td>
<td>&lt;.001</td>
</tr>
<tr>
<td><strong>Core area</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEX</td>
<td>-0.70</td>
<td>0.42</td>
<td>.10</td>
</tr>
<tr>
<td>BREED</td>
<td>-1.24</td>
<td>0.38</td>
<td>.002</td>
</tr>
<tr>
<td>COHETERO</td>
<td>4.39</td>
<td>0.62</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>
DISCUSSION

In this study, we compared space use metrics in two populations of Willow Flycatchers as a function of breeding status and sex. We expected breeding site to have the strongest influence on space use due to differences in habitat structure at Fish Creek and Roosevelt Lake however we found that variation in space use across Willow Flycatchers appears to be influenced by breeding status and flycatcher sex as well as by breeding site.

In the nine space use metrics we examined, only core area habitat heterogeneity did not vary statistically by breeding status, flycatcher sex or breeding site. The lack of variation in core area heterogeneity as a function of flycatcher sex, breeding status or site appears to illustrate Willow Flycatcher’s need to breed in mature riparian habitat. This seems to be especially true for the core areas of females which are almost completely comprised of mature riparian habitat. Heterogeneity shows little variation among flycatchers because the majority of the core area is composed of a single patch of mature riparian habitat. This finding is consistent with previous work that identified little variation in the presence and density of willows at the microplot scale within the territories of Willow Flycatchers (Sedgwick and Knopf 1992).

CORE AREA SIZE

The kernel UD isopleth selected to represent individual flycatcher’s core areas within the home range ranged from 15% to 60% across all Willow Flycatchers we studied with an average kernel UD isopleth size of 35% for female flycatchers and 40% for male flycatchers. Many bird space use studies use a 50% kernel UD isopleth to represent core area (e.g. Elchuk and Wiebe 2003, Vega Rivera et al. 2003). Our use of a rule-based approach to identify core areas suggests that the application of the 50% kernel UD isopleth does not accurately reflect the core area of most Willow Flycatchers. The 50% kernel UD overestimates the size of core area in the home ranges of most the Willow Flycatchers tracked in this study. The accurate delineation of home range core areas is important because behavior has been found to vary in core areas relative to
other parts of the home range (Indermaur et al. 2009; Bakian in preparation). The regular use of the 50% kernel UD is likely done for convenience and to facilitate cross-study comparisons. We found the application of a rule-based core area procedure to be straight-forward and easy to implement in a GIS framework. The use of data distribution-driven approaches to delineate core area boundaries has been suggested elsewhere (Hodder et al. 1998; Barg et al. 2005, Wilson 2010) and we also encourage researchers to use non-arbitrary methods of delineating core areas whenever possible.

**BREEDING FLYCATCHERS**

As we expected, we found that breeding male flycatchers at Roosevelt Lake maintained smaller home ranges than male breeding flycatchers at Fish Creek. We hypothesized a priori that any observed differences in home range size were due to variation in the distribution and structure of breeding habitat at Fish Creek and Roosevelt Lake. Home ranges of breeding males at Fish Creek were more heterogeneous. Home range size has been found to be inversely related to home range quality as home ranges will expand to the point that they encompass resources sufficient to optimize fitness (Harestad and Bunnell 1979). If habitat quality differences are driving home range size in Willow Flycatchers then our findings suggest that breeding habitat at Fish Creek is of lower quality than at Roosevelt Lake. Our findings and more specifically our linear models provide support for the resource-dispersion hypothesis (Macdonald 1983) which predicts that home range size will increase with increasing resource patchiness or heterogeneity.

Riparian habitat patch sizes at Fish Creek are relatively small averaging 1.40 hectares and ranging from 0.29 hectares to 2.5 hectares. In comparison, patch sizes at Roosevelt Lake range from 0.2 ha to 43 ha (Paxton et al. 2007). Previous research with Southwestern Willow Flycatchers has found that they will not nest in mature riparian patches less than 10 meters wide (Sogge and Marshall 2000). In addition, SWFLs have been found to cluster their home ranges into small sections of large mature riparian patches while leaving large stretches of riparian
habitat unused (Whitfield and Enos 1996, Paxton et al. 1997, Sferra et al. 1997). Previous studies have reported minimum patch sizes of 0.6 ha required for selection by Southwestern Willow Flycatchers (Sogge and Marshall 2000). If Willow Flycatchers require buffer zones within habitat patches, then the size of mature riparian patches at Fish Creek may be on the smaller end of the range of patch sizes that Willow Flycatchers will select for breeding. Willow Flycatchers may limit the density within individual patches at Fish Creek to provide adequate buffer zones within patches.

FIGURE 4.4. Relationship between home range habitat heterogeneity and the natural log of home range size (ha) as a function of sex and breeding site: Fish Creek females (pink), Fish Creek males (green) and Roosevelt Lake males (blue). Adjusted $R^2 = .35$. 
Conversely, Fish Creek male flycatchers may maintain larger home ranges because habitat is not a limiting factor at Fish Creek. Population density and home range size are inversely related (Kjellander et al. 2004, Wang and Grimm 2007) and flycatcher density appears to be higher at Roosevelt Lake than Fish Creek. However, it has been reported elsewhere that flycatchers reach their highest densities in mesic sites (Sedgwick and Knopf 1992) such as Fish Creek. Fish Creek flycatcher home ranges may be larger and more heterogeneous because the microclimate transitions at habitat boundaries are less abrupt than at Roosevelt Lake where riparian habitat is bordered by xeric uplands and open areas.

The home ranges and core areas of female breeding Willow Flycatchers were smaller than the home ranges of male breeding Willow Flycatchers at Fish Creek. We suspect that females at Fish Creek maintained smaller home ranges than males at Fish Creek due to behavioral differences during the breeding season. Female flycatchers are required to center their activity around the nest site as they are primarily responsible for nest construction and egg incubation (McCabe 1991). Conversely, a study by Stafford and Valentine (1985) investigating territory sizes in a Willow Flycatcher population in central Sierra Nevada reported larger territory sizes for female than male flycatchers. Although female SWFLs were not sampled at Roosevelt Lake, we predict based on our findings that the core area and home ranges of female SWFLs at Roosevelt Lake are smaller than the core area and home ranges of female and male flycatchers at Fish Creek and male SWFLs at Roosevelt Lake.

NON-BREEDING FLYCATCHERS

In our categorization of breeding versus non-breeding flycatchers, we did not distinguish between territorial flycatchers radio-tracked during pre and post-breeding periods, territorial unpaired flycatchers and floaters due to small sample sizes in the latter two groups. Space use metrics in radio-tracked non-breeding flycatchers did not appear to be influenced by flycatcher sex or population site. This suggests that when flycatchers are free from the energetic costs of
breeding, Willow Flycatchers will expand their home range size. Alternatively, the opposite relationship may exist in which resource availability is more sparse pre and post-breeding and flycatchers are increasing their space use during these periods to meet their resource needs. Estimates of home range size in Willow Flycatchers during the pre and post-breeding stages may also include long-range movements that were conducted to prospect for future territory site establishment (Bayne and Hobson 2001).

**FIGURE 4.5.** Relationship between core area habitat heterogeneity and the natural log of core area size (ha) as a function of sex and breeding site: Fish Creek females (pink), Fish Creek males (green) and Roosevelt Lake males (blue). $R^2 = .51$. 
Home range expansion during pre and post-nesting periods has not been observed in many bird species. Some studies have found home range size to be consistent across pre-breeding, breeding, and post-breeding stages in other neo-tropical migrants (Vega Rivera et al. 2003, Garza et al. 2005) as well as other populations of the Willow Flycatcher (Stafford and Valentine 1985). Given the small sample size of floater and territorial, non-mated paired flycatchers in our Roosevelt Lake study sample, the trends we identified here do not appear to be driven by unmated flycatchers.

We did not test for differences in space use metrics between breeding and non-breeding flycatchers at Fish Creek. As space use metrics were not found to differ among non-breeding flycatchers as a function of breeding site, we feel that the differences observed in space use in breeding versus non-breeding flycatchers at Roosevelt Lake may also be common to Fish Creek flycatchers.

MANAGEMENT IMPLICATIONS

Previous estimates of flycatcher home range and territory size using territory mapping techniques range from 0.3 ha in the Sierra Nevada Mountains of California (Flett and Sanders 1987) to 1.72 ha in the Colorado Rockies (Eckhardt 1979). Problems associated with these studies include their reliance upon territorial mapping using re-sight or recapture techniques and their focus primarily on male flycatchers. Territory mapping techniques may underestimate home range size (Anich et al. 2009) and our findings suggest that this may be the case with Willow Flycatchers. The average home range size for breeding males at Fish Creek is larger than any previously reported estimate of Willow Flycatcher home range or territory size. Willow Flycatchers do not vocalize throughout their home range and are difficult to detect when not vocalizing (Bakian, in preparation). The area defined by male song is more likely to represent the boundary of an individual’s defended territory rather than the home range. Resource use patterns collected within the territory may not represent the resources acquired from the entire home range.
range. The home range size of female flycatchers, who do not sing conspicuously throughout the breeding season, is even more challenging to accurately estimate in the absence of radio-tracking. In this study, we found that home range size varies as a function of breeding site, breeding status and sex. This suggests that multiple characteristics of the population need to be considered when protecting landscape space for Willow Flycatchers during the breeding season as space use shows considerable fluctuation. To accurately determine which mechanisms are responsible for variation in space use, home range characteristics should be considered relative to habitat quality and fitness measures.

Our findings indicate that patterns in space-use among non-breeding Southwestern Willow Flycatchers may be relevant to other populations of non-breeding Willow Flycatchers. This appears to be the case for both male and female non-breeding flycatchers. Patterns in space use in breeding Southwestern Willow Flycatchers do not seem to be generalizable to non-SWFL populations whether male or female. Local factors appear to influence inter-population differences in home range size. Of interest would be to determine if common patterns in space use are observed among breeding Willow Flycatchers inhabiting mesic versus xeric areas. If so, this would suggest that habitat quality for Willow Flycatchers vary as a function of larger scale climatic factors.

LITERATURE CITED


Spatial heterogeneity drives ecological processes and impacts population-level dynamics (Kareiva 1990). Given the wide-spread alteration of natural landscapes currently underway, understanding how wild populations respond to environmental heterogeneity is more important now than ever. The Willow Flycatcher, a neo-tropical migrant, is a species facing population declines throughout much of its range in the western United States (Sedgwick 2000). Environmental heterogeneity may impact Willow Flycatcher population dynamics in a variety of ways including their dispersal and migration, reproductive fitness, resource selection patterns and space use. My research specifically examines the selection of resources for vocalization and foraging by Willow Flycatchers at individual and population-level scales, Willow Flycatcher’s use of aquatic and terrestrial prey subsidies, and variation in space use characteristics in two geographical disparate populations of Willow Flycatchers. In combination, the findings I report illustrate some ways that Willow Flycatchers respond to spatial heterogeneity. In addition, the patterns in resource selection and space use in Willow Flycatchers identified in this study have important species-level conservation and management implications.

In chapter 2, I formulated spatial Bayesian resource selection functions to investigate behavioral resource selection in Willow Flycatchers at individual and population-scales. Results from the individual-level models illustrate the high degree of intraspecific variation in vocalization and foraging resource selection exhibited by Willow Flycatchers. Resource selection functions are often formulated on a population-level ignoring intraspecific variation in selection (e.g. Sawyer et al. 2006, Belant et al. 2010). In addition, wildlife managers typically base their conservation plans on inference derived from population-level studies. However, for species that live in a meta-population like the Willow Flycatcher, species management that is done without
considering intra-specific variation may lead to deleterious effects over the long-term (Pulliam 1988).

Ecologists increasingly use more and more sophisticated analytical tools to model wildlife-environment relationships. They are improving the realism of their models through the use of hierarchical frameworks and the addition of random effects. In chapter 2, I introduced a novel approach to modeling flycatcher behavior using spatial Bayesian resource selection functions. Output from these models was used to produce predictive images of behavior which may be interpreted as “behavioral landscapes.” These behavioral landscapes create the link between space use and behavior; a link that has been largely missing from resource selection and space use research (Lima and Zollner 1996, Marzluff et al. 2001).

Sedgwick and Knopf (1992) investigated differences in habitat selection between male and female flycatchers. They observed variation in habitat selection as a function of sex at the nest and song perch scale. My research further elucidates differences in the ecology of male and female flycatchers. I compared and contrasted resource selection, and space use among male and female flycatchers. Only subtle differences in diet were observed as a function of sex while considerable differences were found in vocalization resource selection and space use characteristics. In general, breeding females require less space during the breeding season than breeding males as indicated by home range and core area size comparisons. Interestingly, this pattern seems to dissolve during the pre and post-breeding periods. Further, males are more likely than females to vocalize from high vegetation perches. Discrepancies in space use among males and females are likely the result of sex-specific differences in behavior during the breeding season (Gowaty 1996, Sedgwick 2000). Sex-based behavioral differences may go largely ignored when managing wild passerines populations yet the accumulation of sex-specific inference improves the feasibility of managing landscapes for both sexes.
I observed that vocalization and foraging often occur in spatially disparate areas of the home range. This suggests that multiple core areas exist within the home ranges of Willow Flycatchers. This finding along with the estimates of core area size I made in chapter 4 using the Seaman et al. (1998) rule shows that researchers need to reconsider their arbitrary use of the 50% kernel UD to represent core area. This is certainly the case for Willow Flycatchers in which core areas appear to be better represented by the 35% to 40% kernel UD than the 50% kernel UD. In addition, the clustered distribution of vocalization behavior indicates that both male and female flycatchers do not vocalize throughout their home ranges. Bird researchers need to be aware of this when conducting census studies based on sight or sound.

Willow Flycatcher’s selection of alternative habitats for foraging at Fish Creek was an unexpected finding. The presence of high-levels of heterogeneity in the flycatcher home ranges at Fish Creek suggests that the availability of multiple habitat types may be important to this flycatcher population. The use of non-riparian habitats by Willow Flycatchers has not been previously documented. This may be the result of Southwestern Willow Flycatcher based studies dominating the literature as SWFLs have not been observed to use alternative habitats for foraging during the breeding season (Cardinal 2005). The use of alternative habitats may be a characteristic of Willow Flycatchers inhabiting mesic zones. Further study is required to determine if this is a common pattern among Willow Flycatcher populations breeding in mesic areas.

My research provides evidence that landscape configuration may be important to Willow Flycatchers breeding at Fish Creek. The diet component of my study demonstrates that Willow Flycatchers consume both aquatic and terrestrial insects. I found evidence suggesting that adult flycatchers are differentially feeding their nestlings predaceous insects. Other Willow Flycatcher studies have observed similar patterns (Prescott and Middleton 1988, Drost et al. 2003, Wiesenborn and Heydon 2007, Durst et al. 2008). At Fish Creek, adjacent habitats such as
mountain shrub, upland forest and open water may produce greater numbers of predaceous insects than the riparian zone. Insect prey derived in alternative habitats bordering riparian habitat may move into the riparian zone to compliment in situ insect production.

This study was conducted in part to determine the relevance of SWFL based studies to non-SWFL populations. My research uncovered considerable differences in space use characteristics between flycatchers as a function of breeding site and breeding status. Breeding status was found to influence home range characteristics as non-breeding flycatchers used larger areas of the landscape than breeding flycatchers. Similar patterns in space use characteristics were observed in non-breeding flycatchers regardless of breeding site. This suggests that Willow Flycatchers use the largest portion of the landscape towards the beginning and end of the Willow Flycatcher breeding season. Conversely, space use patterns have been found to be largely consistent across the entire breeding season in other neo-tropical migrants (Vega Rivera et al. 2003, Garza et al. 2005). Differences in space use among breeding flycatchers as a function of breeding site indicates that it is inappropriate to apply information gleaned from SWFL-based studies to manage non-SWFL populations.

In conclusion, in this study, I tested Willow Flycatcher’s response to environmental heterogeneity, developed a novel modeling approach to analyze behavioral resource selection, and increased our understanding Willow Flycatcher ecology. This was the first study that I am aware of that compared and contrasted space use in different populations of Willow Flycatcher. Finally, future research projects and improved Willow Flycatcher management plans may develop out of this study’s major findings.

LITERATURE CITED


APPENDICES
APPENDIX A

Chapter 2 supplemental material
Fig. A.1. WIFL #1 observed (a) vs. fitted (b) vocalization behavior, and observed (c) vs. fitted (d) foraging behavior.
Fig. A.2. WIFL #1 mean predicted vocalization behavior with prediction grid locations (a), standard deviation predicted vocalization (b), mean predicted foraging with prediction grid locations (c), and standard deviation predicted foraging (d).
Fig. A. 3. Comparison of approaches to visualizing home range space use: 95% utilization distribution (UD, black outline) using a fixed-kernel estimator (a), probability of vocalization behavior within 95% utilization distribution from fitted Bayesian generalized linear spatial model, scale ranges from 0.0 (dark blue) to 1.0 (red) (b), and probability of foraging behavior within 95% utilization distribution from fitted Bayesian generalized linear spatial model, scale ranges from 0.0 (dark blue) to 1.0 (red). Nest site location represented by gold star.
APPENDIX B

Co-authorship permission letter
February 14, 2011

Amanda Bakian  
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Dear Dr. Paxton,

I am in the process of preparing my dissertation in the Department of Biology at Utah State University, and will be completing my degree in March of 2011. Utah State University’s School of Graduate Studies requires all co-authors of dissertation chapters from dissertations written in a multiple-paper format to grant permission to use co-authored materials in dissertations. I am requesting your permission to include the dissertation chapters co-authored by you as shown below. The chapters listed below, as you know, are not currently published in peer-refereed journals. I will use my dissertation to cite the material unless the chapters are published in a peer-refereed journal prior to the completion of my dissertation.

Please indicate your approval of this request by signing in the space provided below.

If you have any questions, please contact me.

Thank you for your consideration,

Amanda V. Bakian

____________________________________________________

I hereby grant permission to Amanda V. Bakian to use the following material in her dissertation:


Signed: [Signature]

Dated: 2/15/11
SUMMARY OF PROFESSIONAL QUALIFICATIONS

- Strong data analysis and problem solving skills
- Effective communicator
- Project management and leadership experience
- Demonstrated team player

Research Experience

- Design and analysis of biological and social science experiments in academic and industry settings.
  - Formulated hierarchical generalized linear mixed models to analyze a spatially explicit animal resource selection database.
  - Conducted a survival analysis of student member cohorts in scientific ornithological societies.
  - Designed a large scale avian and vegetation line transect survey study.

Collaborative Activities and Team Work

- Contributed scientific expertise to research teams in the U.S. and Japan.
  - Conducted numerous research projects in collaboration with National Science Foundation ADVANCE grant principal investigators.
  - Investigated statistical network properties of ecological communities with research team at the University of Kyoto, Japan.
  - Developed a faculty database tracking recruitment, retention, and promotion of USU science and engineering faculty, and assisted USU administrators with database acquisition.

Leadership and Project Management

- Supervised field research crew, undergraduate research assistants, and coordinated research projects.
  - Managed field crew, acquired funding and organized research budget for multi-year animal resource selection study.
  - Supervised undergraduate research assistants in field and laboratory techniques, data entry, independent research projects, and assisted with poster presentation preparation.

EDUCATION

- PhD in Biology/Ecology, Utah State University, Logan, Utah, GPA 3.90 (Expected spring 2011)
- MS in Statistics, Utah State University, Logan, Utah, GPA 3.84 (April 2009)
- BA in Biology, Colby College, Waterville, Maine (May 1998)
Employment History

**Epidemiologist**, Utah Registry of Autism and Developmental Disabilities, Department of Psychiatry, University of Utah, Salt Lake City, Utah (January 2010-Present)
- Autism and developmental disabilities surveillance, risk factor and trend analyses, and database management.
  - Analysis of the sociodemographic and obstetric risk factors associated with autism and intellectual disabilities.
  - Spatial analysis of autism cases.
  - Manage ACCESS database for six member autism abstraction team.

**Graduate Research Assistant**, National Science Foundation ADVANCE Grant: SBE 0244922, Utah State University, Logan, Utah (February 2005-December 2009)
- Conducted multiple studies to investigate career disparities between women and men science and engineering faculty.
  - Analyzed teaching load, job satisfaction, and work productivity differences between men and women faculty using generalized linear, sample comparison, and multivariate statistical models.
  - Formulated deterministic and stochastic matrix models to project changes in women’s representation among science and engineering faculty.
    - Developed a website to host models as an interactive, on-line tool.
  - Crafted a survey to examine differences in career and family expectations between male and female biology/ecology graduate students.
    - Supervised a 5 member survey team at the 2007 Ecological Society of America meeting.
  - Developed and managed a faculty database to track the recruitment, retention and promotion of USU faculty.
  - Conducted a survival analysis of male and female graduate student members of two North American Ornithological Societies to project changes in membership composition.
  - Mentored and evaluated undergraduate student researchers in data collection, analysis, and preparation of research posters.

- Designed observational study to investigate Willow Flycatcher habitat and resource selection.
  - Supervised three field technicians, managed project budget, and acquired project funding.
    - Formulated Bayesian spatial generalized linear mixed models to describe and predict bird behavior.
  - Investigated Willow Flycatcher diet through carbon and nitrogen stable isotope analysis.

**National Science Foundation EAPSI Fellow**, Kyoto University, Kyoto, Japan (June-September 2008)
- Research with Dr. Takayuki Ohgushi investigating the statistical network properties of plant-herbivore ecological communities.
- Selected to serve as alumni representative to the 2009 NSF EAPSI program.

**Biometric Consultant**, Salt Lake City, Utah (February 2006 – Present)
Experimental design and analysis, statistical consulting, and database development for clients.

- Developed an avian and vegetation transect survey study, and formulated avian species distribution models that served as the basis for restoration plans in Teton Valley, Idaho for Intermountain Aquatics, Driggs, Idaho.
  - Built project-specific ACCESS database.
- Developed R tutorials for the Mountain Studies Institute, Silverton, CO.
- Statistical consulting for Utah State University doctoral students.

**Graduate Teaching Assistant**, Department of Biology, Utah State University, Logan, Utah (August 2002- May 2005) Instructed 30-120 students/semester in the following courses:

- Introduction to Biology lab, Human Physiology lab and Ornithology.

**Wildlife Biologist**, various US federal agencies (Spring 1998-August 2002)

- Conducted a population demography study of the federally endangered Southwestern Willow Flycatcher for the US Geological Survey, Flagstaff, AZ.
- Participated in a study of fire effects on cavity nesting birds for the USDA Forest Service, Rocky Mountain Research Station, Boise, ID.
- Worked on a population demography study of the federally endangered Mariana Crow with the US Fish and Wildlife Survey, Rota Island, Northern Mariana Islands.

**COMPUTER SKILLS**

- SAS, R/S+, SPSS, ArcGIS, EXCEL, ACCESS, Program Distance.

**AWARDS and GRANTS**

- NSF EAPSI (East Asian and Pacific Summer Institutes for Graduate Students) Fellowship, 2008
- Datus M. Hammond Memorial Scholarship, Department of Biology, Utah State University, 2007-2008
- Claude E. ZoBell Scholarship, College of Science, Utah State University, 2006-2007
- Graduate Student Symposium Best Paper Presentation, Utah State University, 2004 and 2007
- USU Ecology Center Graduate Student Research Grant, Utah State University, 2003-04, 2005-06, and 2006-07
- Women and Gender Research Institute Grant, Utah State University, 2003
- Frank M. Chapman Grant, American Museum of Natural History, 2003

**PUBLICATIONS**


**SELECTED PRESENTATIONS**


o Sullivan, K.A. and A.V. Bakian. 2008. Work-family decisions during the transition from graduate school to professional scientist. The New Norm of Faculty Flexibility Conference, Iowa State University, Ames, Iowa.


INVITED TALKS

