Bobcats Within a Mosaic of Housing Densities in Connecticut

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Bobcats Within a Mosaic of Housing Densities in Connecticut

Kristen Marie Beattie

B.S, Northland College, 2015

A Thesis
Submitted in Partial Fulfillment of the
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Bobcats Within a Mosaic of Housing Densities in Connecticut

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2020
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Abstract

Understanding a species’ ability to adapt and persist in a human-dominated landscape is important as urban development continues to spread, resulting in wildlife living in close proximity to people. Mesocarnivores are using urban landscapes, yet differences in habitat selection across a species’ range and among urban areas are beginning to emerge. Bobcats are a strict mesocarnivore species that is considered sensitive to fragmentation and intolerant of human activity yet is now living within densely populated areas in some regions. An important first step in understanding bobcat habitat use throughout a range of housing densities is understanding how the effectiveness of monitoring techniques changes from wildlands to urban landscapes. In addition, understanding how to classify and quantify anthropogenic disturbances in relation to how bobcats perceive them across a landscape will allow for a more complete understanding of bobcats within urban landscapes. Lastly, as bobcats occupy developed areas understanding mechanisms, such as how bobcat diet shifts when prey availability and diversity shifts, that allow for persistence within development are important for identifying effective management actions. Through the use of lured cameras, I demonstrated that monitoring techniques’ effectiveness changed across building density as effectiveness of lure type was enhanced in higher building densities. I found that bobcats occupied the full range of housing density from rural to highly suburban landscapes, yet I was able to determine that bobcats did not occupy neighborhoods above 1,000 buildings per km$^2$. Using stable isotopes from hair samples, I found that bobcat diet consisted primarily of natural prey species in natural habitats, throughout backyards, and in developed landscapes; that is, bobcats did not incorporate anthropogenic food sources, such as pets and livestock, into their diet. Overall, I found that bobcats, a top predator in New England, are thriving in this landscape that is forest intermixed with development. From a management
perspective, risks bobcats are exposed to in other regions of the US (e.g., exposure to rodenticides as a result of shifting to rodent prey in urban areas) was not evident in my study. In this region, I found that maintaining a minimum level of core natural habitat within every 1 km² grid cell of the landscape resulted in a mosaic of natural and anthropogenic landcover that bobcats currently occupy. Increased collaboration between wildlife managers and urban planners is needed to design landscapes that continue to allow for the co-existence of both people and wildlife into the future.
Introduction

Mammalian species were over-harvested throughout the 19th and 20th centuries in North America (CT DEEP 2016). Some species became so elusive that they were rarely sighted near human establishments. Due to effective wildlife management and creation of federal laws, some species have increased in abundance and are now found within close proximity to residential housing throughout many developed areas. Although these species now coexist with humans within neighborhoods and parks, places originally designed for humans rather than wildlife, our understanding of wildlife habitat use throughout this type of human-dominated landscape is not well understood. As the realized use of habitats is changing rapidly due to global urbanization (Seto et al. 2012), wildlife species previously untouched by urbanization are adapting to the expansion of anthropogenic landscapes (Ditchkoff et al. 2006). Understanding a species’ ability to adapt and persist in an anthropogenic landscape will be important as urban development continues to spread, and more species are forces to live in close proximity with humans.

Habitat configuration within urban landscapes drastically changes across housing density classifications (i.e., wildland, rural, exurban, suburban, urban) and scientists are beginning to articulate how mammalian populations persist withing these landscapes. Mammalian research is largely based within wildlands. Understanding of urban carnivores has increased greatly in the last decade (Gehrt et al. 2010). For example, medium-sized carnivores, such as raccoons and foxes have adapted to human-dominated urban landscapes (Prugh 2009; Gehrt et al. 2010; Dellinger et al. 2013; Bouyer et al. 2015), and coyotes now live in New York City and downtown Chicago (Gehrt et al. 2009; Nagy et al. 2016, 2017). Many of these carnivores can expand to a more omnivorous diets in urban landscapes. Large, strict carnivores, such as wolves and mountain lions have not been observed to persist in fully urban landscapes, but these species
now occur where urban areas are interfaced with wildlands, and thus individuals make forays into suburban developments (Bateman and Fleming 2012). Black bears, a large, omnivores species, lives withing wildlands and make forays into suburban landscapes (e.g., Reno or Lake Tahoe; Lackey et al. 2013) and also lives within exurban developments with housing densities < 50 houses per km² (e.g., Connecticut; Evans et al. 2017, 2019).

Bobcats are the most wide-ranging felid in North America, found across the U.S., ranging from the Canadian border to Mexico, and from the western coast to the eastern coast (Anderson and Lovallo 2003, Hansen 2007). Bobcat home ranges vary across North America: Idaho 9 to 109 km² (Bailey 1974), Alabama < 4 km² (Miller 1980), and Connecticut female 19.4 km² and male 54.7 km² (Jason Hawley, personal communication). Bobcats are habitat generalists found in forest, shrublands, and deserts (Conner and Leopold 1996), and seasonal shifts in habitat are often due to shifts in prey abundance (Anderson 1987, Sandell 1989, Lovallo and Anderson 1996). As mesocarnivores, bobcats prey on species ranging from 0.7 to 5.5 kg (Anderson and Lovallo 2003). Bobcats typically prey on lagomorphs (Anderson and Lovallo 2003) and large rodents (Beasom and Moore 1977), yet are generalists known to prey on small rodents, birds, reptiles, domestic pets, and livestock (Hunter 2011). In northern regions, bobcats are also known to prey on white-tailed deer (Nelms et al. 2001), depredating fawns and adult deer in poor health. A recent study of deer fawn survival in Connecticut documented fourteen bobcat predation events (40% of fawn mortalities; Kilburn, 2018).

Bobcats, an important furbearer species, were nearly extirpated from Connecticut by 1972 due to human expansion (Litvaitis et al. 2006). Bobcats were designated as a game species by the state of Connecticut in 1972 and have been protected by a closed trapping season since then (CT DEEP 2016), and thus the species has gradually recovered. Two nation-wide
population surveys were completed on bobcats in 1996 and 2008 (Woolf et al. 1998; Roberts and Crimmins 2010, respectively). Bobcats were found to be uncommon in Connecticut from analysis of the 1996 survey that summarized data from across northeastern states (Distefano 1990, Woolf and Hubert 1998), but were found to be increasing in the 2008 follow-up survey (Roberts and Crimmins 2010). Before 2017, methods used to monitor bobcats in Connecticut were limited to publicly reported sightings and analysis of vehicle collisions (Roberts and Crimmins 2010). Overall, bobcat populations have continued to increase since the 2008 survey and human population has doubled since 1981 (USFWS 1981). Roberts and Crimmins (2010) completed their survey because of major changes in terms of landscapes and ecosystems as human population and development have continued to expand beyond historically developed regions. The bobcat population has increased enough that bobcats are now publicly sighted and reported in towns throughout Connecticut (CT DEEP; unpublished data from public sightings and vehicle collisions analysis). We confirmed these sighting by establishing a CT Bobcat Project iNaturalist webpage to encourage more reporting.

Urban bobcat studies have been previously focused in the western U.S. (Harrison 1998; Crooks 2002; Riley 2006; Ordenana et al. 2010; Young et al. 2019). In New Mexico, a study revealed that bobcats are using residential areas (Harrison 1998). In California, multiple studies have documented ways that bobcats can be sensitive to urbanization (Crooks 2006, Riley 2006, Ordeñana et al. 2010). A study in Texas revealed that bobcats are living within the densely populated Dallas-Fort-Worth metroplex (Young et al. 2019). More recently, on the eastern coast, bobcats have been observed occupying exurban and suburban housing throughout Raleigh, NC and Washington D.C (Parsons et al. 2019). These studies span different regions and landscape contexts, and thus consistent patterns regarding bobcats use of urban areas have not yet emerged.
A review paper summarized mesocarnivores living within urban landscapes, and one common mechanism resulted from the direct benefit from anthropogenic food resources (Bateman and Fleming 2012). Red fox (*Vulpes vulpes*) diet in Switzerland was found to contain more than half anthropogenic items, such as garbage and garden material (Contesse et al. 2004), while American black bear (*Ursus americanus*) diet in urban environments is supplemented with seed from bird feeders (unpublished data DEEP). Bobcats are solitary and strict carnivores; therefore they do not exploit anthropogenic resources like garbage, gardens or bird seed that other mesocarnivores species do. Understanding why a species, such as bobcat, that does not directly benefit from anthropogenic food resources chose to live in and persist in urban landscapes will be important to generalizing knowledge on carnivores to other vertebrate groups that also do not consume anthropogenic food resources.

Few studies have addressed bobcat feeding ecology in urban environments, and the abundance and availability of prey species in urban areas may influence bobcats’ occurrence and use of high density areas (Riley 2010). Bobcats in urban areas of northern California rely more heavily on small mammals as a food source than on rabbits and large rodents (Riley 2010). Prey switching behavior is common when the abundance of the primary prey species of a predator declines (Leopold and Krausman 1986). During a time when rabbit abundance was low, bobcat scat analysis showed a diet of rodents and birds (Bailey 1974). Bobcat interactions with prey species are important to understand as the interaction can impact bobcat habitat selection and home range size (Anderson and Lovallo 2003). Further, depredating small mammals in northern California exposed bobcats to rodenticides, resulting in bobcats in poor health (Riley 2010).

The overall goal of my thesis was to understand how bobcats are living within and responding to the unique landscape of Connecticut, where forest is intermixed with urban
development. I focused on describing two patterns that varied across the mosaic of housing densities found in Connecticut. First, I described bobcat occupancy patterns across a full range of housing densities, and second, I determined if bobcats exhibit prey switching behaviors among housing densities. Before I could appropriately assess occupancy rate for bobcat, I first determined how bobcats respond to monitoring methods across the rural-urban gradient. Therefore, the three chapters of my thesis are as follows. In chapter one, I addressed how effective different lures were at detecting bobcats and how lures effectiveness changed with seasons and across building densities. In chapter two, I then described bobcat occupancy and detection within a mosaic of housing densities and this effort demonstrated how housing metrics influenced our understanding of occupancy in urban systems. Lastly, in chapter three, I use stable isotopes ratios measured in bobcat hair and from potential prey species across the urban gradient to understand how biological variables (sex, age, weight), housing density, and seasonality affect bobcat diet.
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Chapter 1: The Effect of Lures on Bobcat (Lynx rufus) Detection Rates Within Exurban Development

Abstract

As developed areas are becoming more prevalent, there is a need to monitor the difference in habitat selection that is occurring amongst and within carnivore species. An important first step is to quantify how the effectiveness of tools and techniques that have been used to monitor species in natural habitats change within developed landscapes. Lures, commonly used to increase normally low detection rates of bobcats, are being utilized to assist in assessing the effect of passive (no lure) verse lured (visual, scent, combination of both) cameras on bobcat detection rates across housing density and seasons. Twenty-eight 1 km$^2$ sample areas were distributed throughout Connecticut from June 2018 to June 2019 via stratified random sample of housing density and randomly assigned a treatment (i.e., passive, visual, scent, and combination of visual and scent) during each sample period (i.e., 24-31 days). A hierarchical multi-season site occupancy model in a Bayesian framework was used to detect changes in bobcat detection rates across three biologically relevant seasons and throughout building densities. Scent lures significantly increased bobcat detection probability above passive cameras and had the highest detection rate (0.083). High building density showed a greater difference in bobcat detection rate among lure types than in low building densities, and there was only a small difference in the effectiveness of lures among seasons. Researchers should consider the influence of landscape type in selecting an appropriate lure for their particular research goals.

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1 Chapter 1 prepared for journal submission with coauthor: Tracy Rittenhouse. Plural pronouns are used to represent the contributions of coauthors in preparation for future publication.
Introduction

Wildlife species have been studied for decades in wilderness and their natural habitats, but urban development is changing landscapes throughout the globe (Lubowski et al. 2006). Wildlife are responding to urban development by changing the habitats that they use (Czech et al. 2000, Miller and Hobbs 2002, Ellis et al. 2010, Estes et al. 2011, Seto et al. 2012), and animal behavior may change as well. The geographical range of coyotes (*Canis latrans*) has greatly expanded outward from the natural areas of the Midwest, and they are now present across the Northeast, including areas densely populated by humans such as New York City (Gompper 2002). As this is one example of a carnivore species that has successful adapted to urban environments, there is a need to monitor the difference in habitat selection that is occurring amongst and within carnivore species. As developed areas become more prevalent and other carnivore species potentially follow the pattern of coyote range expansion in urban environments, human-wildlife conflicts are likely to arise. An important first step to better understand carnivore distribution across gradients of human-impacted landscapes is to quantify how the effectiveness of tools and techniques that have been used to monitor species in natural habitats change within developed landscapes.

Monitoring a carnivore species is difficult due to their large home ranges, cryptic behavior, low densities across the landscape, and avoidance of humans (Balme et al. 2009; Obbard et al. 2010; Ripple et al. 2014). Techniques for monitoring carnivore species include track and sign, scent stations, scat surveys, hair snares, telemetry, GPS collars, and camera traps (trail cameras). When selecting among techniques, researchers must consider the time, effort, and resources needed as well as how invasive the technique is to the animal based on the goal of the research. Trail cameras, initially used by hunters, have been repurposed by researchers (Kelly
and Holub 2008; Rovero et al. 2013) and are an increasingly common tool used in wildlife research (McCallum 2013). Compared to other monitoring techniques, camera traps are more cost, resource, and time efficient (O’Connell et al. 2006, O’Connell et al. 2011). Camera traps can target a wide range of focal species and can provide replication across both temporal and spatial scales (Gompper et al. 2006, Kay and Slauson, 2008)

Carnivore species have low detection rates (O’Connell et al. 2011), and for decades researchers have used attractants to increase detection rates (Schlexer 2008) above random chance (passive) (Stewart et al. 2019). An attractant is any object or substance used to draw in the target species to a monitoring device such as a camera trap or hair snare. An attractant can be in the form of bait (i.e., reward-based) or lure (non-reward-based). Lures come in the form of olfactory (scent), visual, and auditory lures. Scent lures are viscous or liquid odors that draw in target animals through their sense of smell. Visual lures attract animals through sight, generally through hanging a reflective object (Schlexer 2008). Auditory lures use electronic calls to stimulate a response from a target animal by imitating vocalization of prey species or conspecifics (Schlexer 2008). Using attractants is an on-going debate in wildlife research (Stewart et al., 2019) due to its potential to violate closure assumptions of statistical models (Du Preez et al. 2014) and habituate animals (Anderson et al. 2019). Attractant use for civets (Fossa fossana) in Madagascar increased detection rates without violating closure assumptions (Gerber et al. 2012). Habituation is less likely to occur when using lures as opposed to bait (Proctor et al. 2005; Cushman et al. 2006; Kendall et al. 2008). As researchers select a lure or lures, they must consider (1) the goals of their research, (2) biology of the animal, (3) temporal and spatial scale of their study, and (4) landscape or study area considerations. These considerations are important
because the effectiveness of lures may vary spatially, temporally, by species, and across landscapes.

The effectiveness of lures varies on a spatial scale due to the difference in distances at which an animal can perceive the lure. Scent plumes may diffuse over a larger area than visual lures are seen, and thus visual lures are likely most effective at short distances. Seasonality can impact the extent to which these lures are effective. During periods of low vegetation (i.e., winter) visual lures become more pronounced in the landscape (Molsher 2001; Tanner and Zimmerman 2012; Cove et al. 2014). Warmer weather (i.e., summer) causes the odor from scent lure to diffuse over a greater area (Suárez-Tangil and Rodríguez 2017)(Schlexer 2008).

The effectiveness of lures also varies over time. Hanging, shiny lures are most effective in a breeze and natural light (i.e., daytime), and their effect does not decay over time (Molsher 2001; Tanner and Zimmerman 2012; Cove et al. 2014). Scent lures work well during both the day and at night, but can decay overtime (Mills et al. 2019). Each lure type has proven effective in various scenarios so the assumption that the combination of both lures would be most effective is reasonable, yet various studies have disproven this assumption with at least some species (Garbor et al. 1994, Molsher 2001, Cove et al. 2014, Read et al. 2015, Suárez-Tangil and Rodríguez 2017). For example, foxes are more likely to avoid a setup with a scent lure and visual lure than a scent lure alone (Suárez-Tangil and Rodríguez 2017). Hunting tactics vary between carnivore species and may determine which lure is most effective. Felids are ambush hunters, so visual lures may be more effective at attracting them. For example, ocelots (Leopardus pardalis) in Costa Rico were more attracted to a compact disc than the scent lure (Cove et al. 2014).

However, carnivore species with a more developed olfactory sense may be more attracted to scent lures, such as fishers (Martes pennanti) (Long and MacKay 2012). Finally, the spatial scale
at which carnivores respond to lures is also influenced by the identification and avoidance of odors of competitor and predator species (Erlinge and Sandell 1988, Harrington et al. 2009).

Urbanization could result in an increase in novel objects and odors that change the effectiveness of visual lures and scent lures. The purpose of this study is to quantify how different lure types affect wildlife detection rates within a mosaic of exurban development. We focused on bobcats (*Lynx rufus*) because of their wide-geographic range that spans many types of human-modified landscapes and their low detection rates as a result of having large home ranges and elusive behaviors (Gompper et al. 2006, Ruell et al. 2009). Passive sampling (sampling without lures) for this species risks not obtaining enough data to answer research questions. We used a study design based on a three camera-array within a 1 km² circular area, which increased detection probabilities over a single camera (O’Connor et al. 2017) and moves the scale of sampling from the area in front of the camera to a scale more relevant to the movement of animal (Efford and Dawson 2012). We report results for several wildlife species in addition to bobcats, because results from this unique study design may inform future projects. We predicted an increase in detection rates of bobcats at lured cameras compared to passive cameras, with the highest detection rates when scent and visual lures were used in combination. We predicted the effectiveness of scent and visual lure to change independently across season (visual lures being more effective during periods of low vegetation, and scent lure being more effective during colder temperatures) and building density (visual and scent lures being more effective in natural landscapes). In addition, we predicted that other mesocarnivores will not match the patterns observed in bobcats, because of species-specific lures used and the likelihood that other mesocarnivores may avoid bobcats.
Methods

Connecticut is the third smallest state in the U.S. covering 14,360 km$^2$ and has a unique mixture of urban development while also being predominately forested. The developed land of Connecticut takes up 19.2% of the total area, while deciduous and coniferous forest cover defined based on National Land Cover Data (NLCD) layers covers 50% of the state (UCONN Center for Land Use Education & Research 2015). Connecticut’s developed land is dominated by exurban development (62.4%). The rate of new development peaked decades ago, yet the occasional home continues to be built annually and forest loss today is the result of conversion from forest to urban development (United States Department of Agriculture 2014).

We conducted a state-wide bobcat survey using wildlife cameras from June 2018 to June 2019. Our study design was based on random placement of circular sample areas that were 1 km$^2$ in size. The circular sample area contained a three camera-array (i.e., 3 individual camera sites) (Figure 1.1). However, completely random placement of sampling areas throughout Connecticut would likely result in spatial clumping. Spatial clumping could hinder inference to the entire state and would not ensure full representation of the housing densities of interest. Therefore, we used two levels of stratification. First, we divided Connecticut into four quadrants by major interstate highways: northwest, northeast, southwest, and southeast. Second, we stratified on housing density from 0-1,000 housing units per km$^2$, sectored into five housing density categories: 0-200, 200-400, 400-600, 600-800, 800-1,000 housing units per km$^2$. We classified housing density using the US Census Bureau 2010 TIGER census block group data (US Census Bureau 2010). From the block group data, we removed block groups that had a housing density greater than 1,000 housing units per km$^2$, that were less than two km$^2$, and those with linear shapes that could not fit a one km$^2$ circular sample area in its boundaries. We then randomly
selected 28 block groups ensuring the following conditions were met. Each quadrant of Connecticut had at least one sample area in each of the five housing categories. Three sample areas that represented 0-200 housing units per km$^2$ were placed in each quadrant of the state because 64.2% of the state of Connecticut is this exurban housing density. We chose not to sample the urban classification (i.e., > 1,000 housing units per km$^2$) assuming that this level of urbanization would preclude bobcats, and rural blocks (i.e., < 6 housing units per km$^2$) were not sampled because there were not enough available blocks to randomly sample. Following random placement of sample areas, we ended up with twelve sample areas classified as exurban and sixteen sample areas classified as suburban following Theobald’s (2005) classification.

Each of the 28 sample areas was divided into thirds, and one camera was placed in each third in a nonrandom location (Figure 1.1). We sought out the most suitable habitat for bobcats and were occasionally limited by access to private land. Cameras were placed on all landownership types: private, commercial, public, town or state owned. The 84 cameras (Bushnell Aggressor 20.0 MP Low Glow Trophy HD Trail Camera) ran continuously for a year, and we monitored them monthly to check for functionality including status of SD cards and batteries. We locked cameras to a tree, 0.5 m off the ground, and facing northward. Cameras were motion-triggered, set on normal sensitivity, and captured a series of three images at one second interval with a thirty second delay between image clusters.

We used four different treatments with two lure types to test the effectiveness of lures on detection rates: passive (no lure), visual, scent, and combination (visual and scent). The visual treatment was a large turkey wing feather attached to a metallic CD hung on a branch 1.5 m above ground between 3 to 6 m in front of the camera. The scent treatment was a mixture of commercial scent lures applied to a mechanical paper towel cloth and partially covered with a
plastic drinking cup to protect the scent lure from environmental conditions that may degrade the smell. We positioned two cloths in front of a camera. One cloth was on a stake 3 m in front of the camera and 1 m off the ground and the second hung on a tree between 3 to 6 m in front of the camera and 1.5 m above the ground. The stake scent lure was a mixture of a 2.5 ml of beaver oil and a 1.25 ml of cat rub, and the hung scent lure was a mixture of a 2.5 ml of beaver oil and a 2.5 ml of bobcat glands. The combination treatment included both the visual lure and the scent lure placed in front of a camera. All hung lures were placed within 30 degrees of camera line of sight (Figure 1.2).

Only one treatment was applied to the entire 3-camera array within a circular sample area during a sampling period of approximately one month (24 to 31 days). Lure treatment within a circular sample area changed among sampling periods. Treatments were randomly assigned in the first four months and then followed that same order for the duration of the study. During a sampling period, all treatments were applied within each housing density category. The lowest housing density category had more sample areas in each time period, and thus each treatment was replicated three times within each sampling period. Each treatment was repeated at least four times in each quadrant for each housing category and at least twelve times for the lowest housing density.

Images were cataloged and processed using the CPW Photo Warehouse Microsoft Access Database, created by Colorado Parks and Wildlife (Newkirk 2016). A single observer identified species in each photo. A detection event was defined as a single species observed in a 30-minute period within the three-camera array (i.e., not individual cameras).

We modelled occupancy in a hierarchical Bayesian framework. Occupancy models are comprised of two parts: occupancy ($\psi$), the probability of a site being occupied, and detection
(p), based on presence (1) and absence (0) data y. Occupancy models are replicated over time (survey) j, and space (site) k, while a multi-season model includes replication over seasons k. A multi-season occupancy model is a linked two-level random effect model comprised of an ecological process (Equation 1) and observation model (Equation 2):

1. \( z_{i,k} \sim \text{Bernoulli}(\psi_{i,k}) \)
2. \( y_{i,j,k} \sim \text{Bernoulli}(z_{i,k}p_{i,j,k}) \)

We modelled occupancy and detection with a Bernoulli distribution. Multi-season occupancy models allow for occupancy to change across seasons but assumes closure among surveys. Multi-season occupancy models have three parameters: (1) initial state occupancy \( \psi_1 \), (2) local colonization (\( \gamma \)), and (3) local extinction (\( \varepsilon \)). For this study, we primarily focused on the influence of lures on detection probability, therefore we modelled no covariates on the occupancy parameters. We ran each model in JAGS (Su and Yajima 2015) in R (R Core Team 2017), with three parallel chains with 300 burn-in and 100,000 iterations. We assessed convergence using an r-hat value <1.1.

We modelled detection probability for bobcats in Connecticut using a multi-season model. We defined seasons by three biologically relevant periods to bobcats: breeding (1 January – 14 April), kitten rearing (15 April – 31 August), and fall (1 September – 31 December). Bobcat movement increases in the fall as the mother and kittens make larger movements together and dispersal may occur. Survey length was defined as one day and thus varied by season: breeding (104 days), kitten rearing (139 days), and fall (122 days).

We used a random intercept coefficient model on detection to model housing density interacted with lure type across seasons. The Microsoft Building Footprint layer (Microsoft US Building Footprint 2018) became available after cameras were deployed and better reflected urban developments within the circular sampling areas than the census data. For example, one
circular sampling area within 800-1,000 housing units according to the census block data had only 270 buildings per km² (Figure 1.3). Therefore, we calculated the number of buildings in each sample area using ArcGIS (Environmental Systems Research Institute 2014), rather than maintaining the original classification based on census data. We used this building density calculation as the measure of urban development in all analyses.

In addition to bobcats, we modelled detection probability for four additional mesocarnivore species: coyote, fisher, grey fox (*Urocyon cinereoargenteus*), and red fox (*Vulpes vulpes*). We used a single-season model for each species, and we defined survey length as one day. We modeled each lure (passive, scent, visual, combination) as a covariate on detection for each mesocarnivore species and for bobcats. For the bobcat model, we also modeled detection at scent lures during week 1, 2, 3, and 4 after the treatment was applied. We removed all detections on the transition days (i.e., the day we visited cameras to replace lure types).

**Results**

From June 2018 to June 2019, we collected 610,130 images and recorded 52,664 detection events. We identified 30 mammalian species, grouping mice and rats into small mammals. All birds except for domestic chickens and wild turkeys were categorized as bird spp. Over the study, we recorded 3,871 human detection events and 2,247 domestic pet and livestock detection events categorized as goat, horse, cow, chicken, domestic dog and cat.

We recorded 654 bobcat detection events over the three seasons: 234 detection events during kitten rearing season, 244 events in the fall season, and 176 events during the breeding season. Bobcat average occupancy probability over the three seasons was 0.89, with an occupancy probability of 0.968 (95% CI = 0.887 - 0.999) during fall, 0.834 (95% CI = 0.686 - 0.946) during breeding season, and 0.864 (95% CI = 0.727 - 0.955) during kitten rearing.
Scent and combination lures had higher detection probabilities than passive cameras based on the non-overlap of 95% confidence intervals. Passive camera detection probability was 0.048 (95% CI = 0.040 - 0.057), combination lure 0.069 (95% CI = 0.059 - 0.079), and scent lure 0.083 (95% CI = 0.070 - 0.094). Visual lures had the same effect on bobcat detections as passive cameras ($\rho$= 0.048, 95% CI = 0.039 – 0.057) (Table 1.1). Scent lures were effective at increasing detection probability until the third week (week 1: $\rho$= 0.0.89, 95% CI = 0.068 - 0.110; week 2: $\rho$= 0.092, 95% CI = 0.070 - 0.117; week 3: $\rho$= 0.079, 95% CI = 0.060 - 0.102; week 4: $\rho$= 0.072, 95% CI = 0.052 - 0.094) (Figure 1.4).

Across all seasons and building density, no lure treatments were more effective than the passive treatment (Table 1.2, 95% CI overlapped). Combination lures during the breeding season were the only treatment to have lower detection probability in high building density than low building density. At low building density, scent lures had the highest detection probability during kitten rearing and fall seasons, but during the breeding season, combination lures had the highest detection probability. At high building density, combination lures had the highest detection probability during kitten rearing, scent lures during breeding, and passive lures in the fall season (Table 1.2, Figure 1.5).

We recorded 2,756 detection events for four other mesocarnivores species: 176 fisher, 582 grey fox, 848 coyote, and 1,150 red fox detection events. Coyote occupancy probability was 0.967 (95% CI = 0.877 – 0.999), red fox occupancy probability was 0.902 (95% CI = 0.786 – 0.976), grey fox occupancy probability was 0.703 (95% CI = 0.531 – 0.849) and fisher occupancy probability was 0.401 (95% CI = 0.247 – 0.580) over the study period (Table 1.1). In contrast to bobcats, no lure treatment was more effective than the passive cameras in detecting fisher, grey fox, coyote, red fox. Detection probability was greatest at combination lures for
coyotes ($\rho=0.099$) and scent lures for red fox ($\rho=0.136$), grey fox ($\rho=0.094$), and fishers ($\rho=0.057$) (Figure 1.6).

**Discussion**

As carnivores use more urban areas, confirming that monitoring tools and techniques used in natural habitats will be effective across the range of urban environments is important for making informed management decisions. Our study revealed that lured camera setups increased detection probability of bobcat over passive camera setups, but the amount of increase varied based on season and building density. For example, we observed a greater difference in bobcat detection probability between lure types at high building density than at low building density.

Scent lures increased bobcat detection probability over passive cameras and had the highest detection rate ($\rho=0.083$). Researchers use scent lures in conjunction with hair snares because scent lures solicit sniffing, rubbing, and rolling behaviors (McDaniel et al. 2000; Weaver et al. 2005). We used a dual placement of scent lure, one raised and one setup at bobcat height. Raising the scent lure may improve its effectiveness because the scent diffused farther (Schlexer 2008), while the lure on the ground draws the animal directly in front of the camera to interact with the lure (Suárez-Tangil and Rodríguez 2017). Researchers using scent lures must select a frequency at which to replace lures. Trapping was historically done with live traps which are visited frequently (e.g., daily). Studies testing effectiveness of lures or baits, as well as culture knowledge shared within the trapping community, are founded on experiences with frequent visits to traps. Camera trapping is vastly different from trapping due to benefit in increased spatial and temporal scale that current data storage and battery capabilities provide. Yet, researchers concerned about low detection still tend to select high frequencies to replenish lures, such as every 3-7 days (Monterroso et al. 2011, Hogue and Hayes 2015, Parsons et al. 2015).
Here, we ran our scent lures for a month and modeled how detection at scent lures changed based on the number of weeks after initial placement (scent week 1, scent week 2, scent week 3, scent week). We found that scent lure remained effective over passive cameras for up to three weeks after initial placement and detection probability increased from week 1 to week 2. We attempted to model how detection changed based on the number of days post scent placement. These models were uninformative due to limited sample sizes on any given day that resulted in a large amount of uncertainty around the estimates. We conclude that the scent lures are the most effective lure for bobcats and remained fully effective for at least three weeks. By the end of forth week, the effectiveness of the scent lures had declined to the level that warrants the scent being replenished.

Although felids are considered to be visual hunters, we showed that bobcats were not attracted to visual lures, as detection rates at visual lures were similar to passive cameras. The Connecticut landscape is primarily forest, which may decrease the visibility radius of these lures making them less effective. Visual lures may have the same detection rate as random chance capture (passive cameras) because they do not solicit a strong response from the animal that pulls them directly in front of the camera like other lures do (McDaniel et al. 2000; Weaver et al. 2005). Though visual lures did not increase bobcat detection across the year in this region, visual lures may be more effective in more open systems, such as the desert in the southwestern U.S. While the combination lure was more effective than visual lures, the combination was not more effective than scent lures. The addition of the second lure did not deter bobcats as some studies have seen with some species (Garbor et al. 1994, Molsher 2001, Cove et al. 2014, Read et al. 2015, Suárez-Tangil and Rodríguez 2017), but the second lure added time, resources, and effort, while not improving detections.
We found small changes in the effectiveness of lures among seasons, especially in low building density. The biggest seasonal difference occurred during the breeding season at scent lured cameras in high building density. Bobcats breed during the winter in Connecticut, and studies have shown that the animals are more likely to approach scent stations during the wintertime (Long and MacKay, 2012), which aligns with our observations. Bobcats are more active during the fall and breeding seasons than during kitten rearing, and we did detect small increases in detection rates at passive, scent, and visual treatments during the fall and breeding seasons at high building densities. In addition, visual lures were slightly more effective during the fall and breeding season as visual lures become more apparent in the landscapes during the occurrence of leaf off (i.e., fall) and in periods of low vegetation (i.e., winter).

Our plots of detection depicted differences among building density. We found a greater difference among lure types in high building density compared to low building density. An explanation for higher detection probability at high building density is that in sample areas that encompasses more buildings, habitat is restricted by impervious surfaces limiting the available habitat bobcats can move through (Chapter 2). Both scent lured cameras and passive cameras produced detection rates that varied across building density and season. The pattern was similar for both lures, while scent lures generally increased bobcat detection compared to passive cameras. We conclude that estimating detection probability is important when using either scent or passive lures in urban landscapes. Visual lures had the smallest change among building density across all seasons (0.013). Thus, visual lures may be the least biased across building density, but visual lures were also the least effective and never more effective than passive lures. Combination lures were the least consistent among building density and season. Combination lures increased from low to high building density during kitten rearing, are similar across density
in the fall, and decrease from low to high building density during the breeding season. Bobcats may be exhibiting avoidance behaviors of multiple lures during breeding within high building densities. We suggest that combination lures should not be used because they showed the most variation across season and building densities and were never more effective than a single lure.

Lures are most useful when they increase the target species without increasing non-target species. Our study showed that none of the lured treatments greatly increased detection rates over the passive treatment of the four competitor species. Studies have shown that carnivores are able to detect other competitor species by smell (Erlinge and Sandell 1988, Harrington et al. 2009). We expected that using bobcat specific lures would deter other mesocarnivore species, yet we did not find this to be the case. None of the mesocarnivores avoided the scent lure, and red fox, grey fox, and fishers were detected most at the scent lure and coyotes were detected most at combination lures. Although the scent lure contained scents specific to attracting other bobcats (i.e., bobcat glands, catrub), the scent lure was used in combination with scents including beaver oil which is known to attract many species (Schlexer, 2008). Alternatively, bobcat scent maybe encountered frequently enough within exurban development that mesocarnivores do not avoid the scent of bobcats. Furthermore, we estimated daily detection rates, while mesocarnivores might response to bobcats only on shorter timescales.

We found that bobcat occupancy was high (28 out of 28 sample areas occupied, Ψ = 0.968) across all three biological seasons (breeding: 0.864, kitten rearing: 0.834, fall: 0.968) and higher than originally anticipated. Occupancy probability was highest in fall, when mothers and kittens make larger movements and kittens begin to disperse. We observed bobcats occupying the full range of urban development sampled, from exurban (7-123 housing units per km²) to suburban (124-989 housing units per km²) (Refer to Chapter Two for additional information on
occupancy). Other studies reported that bobcat occupancy decreased with an increase in development (Riley 2006, Ordenana et al. 2010, Goad et al. 2014, Wang et al. 2015), opposite the pattern we observed. We suggest that our use of lures does not bias our estimates of occupancy because the occupancy estimates are at a spatial scale of 1 km$^2$. The lures were used to attract bobcats already in the 1 km$^2$ sample area to trigger the cameras. Lures are not likely to influence bobcats found outside the sampling areas.

As carnivores shift their range to more urban environments, researchers should consider if the monitoring techniques used in natural environments will continue to be the most effective within developed landscapes. We demonstrate that understanding the landscape in which the research is being conducted is important in determining the type of lure to use. As studies span a range of housing densities, as ours did, lures may be more effective at attracting the target species at one end of the housing density gradient than the other. When sampling across a housing development gradient where carnivore species are equally spread across the landscape, the use of certain lures may bias detections towards urban environments. When a species occurs in low density within urban areas, the use of lures may more effectively to detect these species in urban environments. Our study reaffirmed that when selecting a lure, researchers should consider their target species and temporal scale while emphasizing the importance of the landscape and research goals in selecting an appropriate lure for their study.
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Su, Y.-S., and M. Yajima. 2015. R2jags: Using R to Run “JAGS.”


Table 0.1. Estimated detection probabilities for coyotes, red fox, grey fox, fisher, and bobcat with 95% credible intervals.

<table>
<thead>
<tr>
<th>Lures</th>
<th>Bobcat</th>
<th>Coyote</th>
<th>Red fox</th>
<th>Grey fox</th>
<th>Fisher</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passive</strong></td>
<td>0.048 (0.040 – 0.057)</td>
<td>0.086 (0.076 – 0.099)</td>
<td>0.119 (0.108 – 0.133)</td>
<td>0.078 (0.066 – 0.090)</td>
<td>0.033 (0.022 – 0.045)</td>
</tr>
<tr>
<td><strong>Visual</strong></td>
<td>0.048 (0.039 – 0.057)</td>
<td>0.067 (0.058 – 0.077)</td>
<td>0.115 (0.101 – 0.129)</td>
<td>0.068 (0.058 – 0.081)</td>
<td>0.044 (0.032 – 0.058)</td>
</tr>
<tr>
<td><strong>Scent</strong></td>
<td>0.083 (0.070 – 0.094)</td>
<td>0.092 (0.081 – 0.103)</td>
<td>0.136 (0.122 – 0.150)</td>
<td>0.094 (0.082 – 0.108)</td>
<td>0.057 (0.043 – 0.073)</td>
</tr>
<tr>
<td><strong>Combination</strong></td>
<td>0.069 (0.059 – 0.079)</td>
<td>0.099 (0.088 – 0.112)</td>
<td>0.133 (0.119 – 0.147)</td>
<td>0.092 (0.078 – 0.105)</td>
<td>0.050 (0.038 – 0.065)</td>
</tr>
</tbody>
</table>
Table 0.2. Estimated bobcat detection probability at low and high building density across season for each lure type with 95% credible intervals.

<table>
<thead>
<tr>
<th>Lures</th>
<th>Breeding Low</th>
<th>Breeding High</th>
<th>Kitten Rearing Low</th>
<th>Kitten Rearing High</th>
<th>Fall Low</th>
<th>Fall High</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.041</td>
<td>0.141</td>
<td>0.062</td>
<td>0.088</td>
<td>0.046</td>
<td>0.111</td>
</tr>
<tr>
<td></td>
<td>(0.026 – 0.062)</td>
<td>(0.078 – 0.238)</td>
<td>(0.044 – 0.085)</td>
<td>(0.050 – 0.142)</td>
<td>(0.032 – 0.065)</td>
<td>(0.068 – 0.170)</td>
</tr>
<tr>
<td>Passive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.052</td>
<td>0.058</td>
<td>0.048</td>
<td>0.045</td>
<td>0.062</td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>(0.034 – 0.077)</td>
<td>(0.026 – 0.111)</td>
<td>(0.033 – 0.070)</td>
<td>(0.030 – 0.067)</td>
<td>(0.031 – 0.111)</td>
<td>(0.024 – 0.089)</td>
</tr>
<tr>
<td>Visual</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.042</td>
<td>0.212</td>
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<td>0.078</td>
<td>0.071</td>
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<td></td>
<td>(0.026 – 0.064)</td>
<td>(0.127 – 0.328)</td>
<td>(0.045 – 0.088)</td>
<td>(0.044 – 0.128)</td>
<td>(0.051 – 0.095)</td>
<td>(0.066 – 0.173)</td>
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<tr>
<td>Scent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>0.060</td>
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<td>0.050</td>
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<tr>
<td></td>
<td>(0.039 – 0.091)</td>
<td>(0.011 – 0.076)</td>
<td>(0.020 – 0.048)</td>
<td>(0.073 – 0.198)</td>
<td>(0.032 – 0.067)</td>
<td>(0.024 – 0.090)</td>
</tr>
<tr>
<td>Combination</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 1.1 Sample area locations (2018-2019) stratified by US Census block group (left), one km² sample area (top right), 3-camera array in divided sample area (bottom right). Note the census block groups differ in size and thus we did not sample blocks (white areas) that had a housing density greater than 1,000 housing units per km², that were smaller than two km², and those with linear shapes that could not fit a one km² circular sample area within their boundaries. Circles were randomly located within the states given two levels of stratification, whereas camera locations were chosen based on best available bobcat habitat.
Figure 1.2. Example of camera station setup with combination lure
Figure 1.3. Comparison of US Census Bureau and Microsoft Building Footprint based on an example sample area classified at 200 – 400 housing units per km$^2$ that contained 106 buildings (left) and an example sample area classified at 800 – 1,000 housing units per km$^2$ that contained 270 buildings (right). When we stratified based on census data, these two examples were classified as very different but using the building layer these two examples are classified as having similar housing densities. Because stratification was based on census data up to 1000 housing units, the highest housing density sampled in this study ended up being only 289 buildings per km$^2$. 
Figure 1.4. Estimated effect of lures type on bobcat detection probability, including how effects of scent lures changed among weeks.
Figure 1.5. Estimated effect of lures (column) based on season (row) and building density on bobcat detection probability. Building density is mean-center and ranges from 0 to 289 buildings per km².
Figure 1.6. Estimated effect of lure type on grey fox (top left), red fox (top right), fisher (bottom left), and coyote (bottom right).
Chapter 2: Bobcats Live Near People in Exurban Neighborhoods and Occupy Suburbs with Connector Habitats

Abstract

As carnivores become more prevalent in landscapes dominated by urban development, identifying and classifying the urban development appropriately is important to understand how carnivores use habitat within exurban, suburban, and urban settings in different ways. To understand bobcat occupancy in human-dominated urban landscapes imbedded within the forest of Connecticut, we conducted a trail camera study stratifying sample areas by the Microsoft Building Footprint Layer. Twenty-five 1 km$^2$ sample areas from September 2019 to December 2019, each containing a three-camera trap array, were randomly placed throughout Connecticut. A hierarchical single-season site occupancy model in a Bayesian framework was used to detect changes in bobcat occupancy and detection rates. Bobcats occupancy was high within exurban landscapes and decreased with building density above 700 buildings per km$^2$ in Connecticut. We found that bobcats are thriving within exurban developments while also occupying high suburban landscapes when there is a minimum of 0.1 km$^2$ of natural area within a 1 km$^2$ area.

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$^2$Chapter 2 prepared for journal submission with coauthor: Tracy Rittenhouse. Plural pronouns are used to represent the contributions of coauthors in preparation for future publication.
Introduction

The awareness that large carnivores, such as mountain lions and leopards, live and move among houses within human-dominated landscapes has changed our understanding of predators in intermixed systems (Gehrt et al. 2010). For example, mountain lions in southern California were reclassified from habitat specialists to habitat generalists (Burdett et al. 2010; Kertson and Spencer 2011; Wilmers et al. 2013) due to large home ranges that overlap densely populated suburban-urban areas (Gehrt et al. 2010, Burdett et al. 2010). Although their home range includes urban areas, mountain lions select against developed areas and make forays into suburban neighborhoods where they forage on smaller prey items (Prange and Gehrt 2004; Smith et al. 2016a). Coyotes use similar habitats as mountain lions, yet differences are being found among regions of the U.S. Coyotes in Chicago select for urban green spaces and avoid development (Gehrt et al. 2009), whereas coyotes in New York are colonizing areas with limited green space (Nagy et al. 2016, 2017). Tolerance towards urbanization varies between species, may be dependent on landscape-level factors, and vary with the scale of urban development.

Researchers in the wildlife field have been classifying housing density and human population using the U.S. Census Bureau data to explain the effect of urbanization on wildlife species (Linnell et al. 2001; Treves et al. 2004; Zielinski et al. 2005; Kretser et al. 2008; Evans et al. 2017; Poessel et al. 2017). The U.S. Census Bureau data of housing includes information on count of housing units and count of residents living in the United States. Urbanization has also been classified based on road density and amount of impervious surface (Fortel et al. 2014; Weaving et al. 2014). In more recent years, housing density has been classified using digitized satellite imagery of developments (Smith et al. 2015, 2016). In 2018, Microsoft released a layer for all the building footprints in the U.S. created from digitized satellite imagery (Microsoft U.S.
Building Footprint 2018). As carnivores become more prevalent in urban landscapes, it is important to identify and classify the urban development appropriately, using ways that most align with how wildlife perceive anthropogenic features.

Buildings and roads are types of impervious surfaces that carnivores do not live on, and thus these features in developed areas fragment the landscape and create isolated patches of natural or useable habitat. As these patches of habitat in urban settings become more restricted and lose connectivity to surrounding natural areas, urban areas experience a loss of biodiversity (Wilcove et al. 1998; Dobson et al. 2006; Crooks et al. 2011). Due to carnivore species’ large home ranges and sensitivity to human activity, connectivity and urban green spaces are needed for carnivores to persist in urban landscapes. Urban connectivity can be achieved through railroad tracks, power lines, and urban city parks (Lewis et al. 1993). As the remaining habitat becomes restricted, species will concentrate on the remaining suitable habitat creating funnel points and high-density areas of urban species (Červinka et al. 2013; Lewis et al. 2015).

Urban areas can provide synanthropic prey species with anthropogenic resources, suitable habitat, and protection from wildland predators. As urbanization increases, the diversity of prey species decreases, whereas the abundance of remaining prey species increases (McKinney 2006, 2008). The high abundance of synanthropic prey species and domestic pets in urban settings may attract carnivore species into more developed areas. In California, coyotes are supplementing their natural diet in urban settings with domestic cats, while in Chicago rodents comprised 42% of the urban diet of coyotes (Morey et al. 2007). Strict carnivore species, such as mountain lions, are also taking advantage of high density of prey and feeding on small prey species in urban settings, such a domestic cats, raccoons and opossums (Smith et al. 2016). Thus, the high density
of prey may allow carnivores to persist in urban areas and likely explains occupancy patterns within urban areas.

Understanding the different ways that carnivores use various levels of urbanization will be important in future management of these species as development continues to expand (Goad et al. 2014). Most mesocarnivores, such as raccoons and red fox, are omnivores and thus are well adapted to urban landscapes, which provides a variety of anthropogenic resources and protection from hunting (Bateman and Fleming 2012). Some mesocarnivores occupying urban landscapes are true predators. Bobcats are strict carnivores and solitary, and due to these traits, may be more sensitive to increased developed areas (Goad et al. 2014). Nonetheless, as medium-sized carnivores and habitat generalist, bobcats may persist or even thrive in urban settings. In New Mexico, a study revealed that bobcats use residential areas (Harrison 1998). Yet, in southern Illinois, bobcats avoided human developments (Nielsen and Cooper 2012; Riley et al. 2010) and in southern California, bobcat occurrence decreased with increasing proximity and intensity of urbanization (Ordeñana et al. 2010). Bobcats are active foragers that continually move through the landscape when foraging. These studies span different regions and landscape contexts, which may be why consistent patterns regarding bobcats use of urban areas has not yet emerged.

Our goal was to determine when high building density precluded the presence of bobcats. We used a newly available building layer instead of the more commonly used housing data from the U.S. Census data to describe bobcat occupancy within an urban landscape that is predominately exurban (7-123 houses per km$^2$) with suburban (124-989 houses per km$^2$) and urban (>989 houses per km$^2$) neighborhoods occurring throughout the landscape. We expected to see a nonlinear pattern in occupancy and that landscape factors and presence of prey would influence bobcat occupancy within this landscape. Suburban and urban areas within the
landscape that contain dense buildings and parking lots have reduced vegetation cover and may restrict bobcat movements to the few remaining places with any vegetation cover. Furthermore, our study design using a camera array may enhance our ability to place cameras in these same remaining green species that act as bobcat corridors or funnels, and thus we predicted that landscape configuration would promote the detection of bobcats.

**Methods**

The study area was Connecticut, a state with predominately natural landcover, which is also a uniquely intermixed system of forest and urban development. Forest covers 50% of Connecticut while developed areas comprise less than 20% (UCONN Center for Land Use Education & Research 2015). Connecticut’s developed landscape is dominated by exurban development covering 62.4% of the developed lands (rural 15.8%, suburban 21.6%, urban 0.2%). The rate of new development peaked decades ago, yet the occasional home continues to be built annually and forest loss today is the result conversion from forest to urban development (United States Department of Agriculture 2014).

We conducted a camera trap survey of bobcats throughout Connecticut from September 2019 to December of 2019, which corresponds with a biological period of increased mobility for mother and kittens, and dispersal occurs. We stratified our site selection using building density. We created a 1x1 km grid covering the state of Connecticut using the fish net tool in ArcGIS 5.1 (Environmental Systems Research Institute 2014). We calculated the number of buildings in each grid cell using the US Building Footprint layer developed by Microsoft (Microsoft US Building Footprint 2018). The number of buildings per grid cell ranged from 0 to 1,357 buildings per km². We sectored the building gradient into 28 equal sections and randomly selected one grid cell from each category (Figure 2.1). No grid cells fell within 1,300-1,350 buildings per km², and
we could not obtain permission for three grid cells above 1,250 buildings per km² and thus the study includes 25 sample areas (Figure 2.1).

Each sample area was a 1 km² grid cell with a 3-camera trap array (3 individual camera sites). We use a total of 75 cameras (Bushnell Aggressor 20.0 MP Low Glow Trophy HD Trail Camera). Cameras were placed in the area that we determined as the most suitable bobcat habitat available, which in some cases was the only available open space in the grid cell. We placed cameras on a suite of ownership types, including private, public, town or state-owned, and in a few instances were limited by access to properties. We locked cameras to a tree, facing northward, and 0.5 meters off the ground. Cameras were motion censored. We set cameras to normal sensitivity, and to capture a series of three images at one second interval with a thirty second delay between image clusters. We set scent lures throughout each sampling area for the full study period, following the same protocol for scent lures of Chapter One, with changes to the quantities of scent lures (all 1.25 ml). Cameras were monitored monthly (i.e., 24 to 31 days) to check SD cards and refresh batteries and lures.

A single observer cataloged and processed all images using the CPW Photo Warehouse Microsoft Access Database, created by Colorado Parks and Wildlife (Newkirk 2016). Species were identified in each photo. A detection event was defined as a single species observed in a 30-minute period within the three-camera array (i.e., not individual cameras). For each sample area, we calculated the number of detections per trap night for two common bobcat prey species: cottontails (*Sylvilagus* spp.) and Eastern grey squirrels (*Sciurus carolinensis*) (Chapter 3).

At the scale of the sample area, we considered three landscape variables: core area largest patch index, proportion of fragmented land to total natural area, and latitude. We used the regional landcover data produced by the NOAA Coastal Change Analysis Program (C-CAP)
(National Oceanic and Atmospheric Administration 2020) to classify natural areas at 10 m resolution. We defined natural areas as all forest cover (deciduous, evergreen, mixed), grasslands, shrubland/scrubland, and all wetland classifications (palustrine and estuarine forested, palustrine and estuarine scrubland/shrubland, palustrine and estuarine emergent). We used morphological spatial pattern analysis (MSPA) within the GuidosToolBox 2.9 (Soille and Vogt 2008; Vogt and Ritters 2017) to classify natural areas within a 500 m buffer around sample areas to avoid classification bias. Natural areas were classified initially into seven morphological types with an edge width of 10 m: core (large interior patches), islet (isolated, small patches), loop (connects same large interior patch), bridge (connects separate large interior patches), perforation (inside perimeter of large interior patch), edge (outside perimeter of larger interior patches), and branch (extension of land with one end not connected). We reclassified islet, loop, bridge, and branch morphological types into a connector landscape type. We calculated two class metrics, largest patch index and total class area, using Fragstats 4.2 (McGarigal and Marks 1995). The largest patch index ranges from 0 (largest patch is increasingly small) to 100 (largest patch is the entire landscape) and was calculated for the core type within each sample area. We calculated the total proportion of the connector type within each sample area. In addition, we considered latitude of the center of each sample area. We found no collinearity between these variables, using \( r = \pm 0.7 \) as a threshold to determine collinearity (Dormann et al. 2013).

Occupancy models are comprised of two parts: occupancy (\( \psi \)), the probability of a site being occupied, and detection (\( p \)), based on presence (1) and absence (0) data. Occupancy models are replicated over time (survey) \( j \) and space (site) \( k \). A single-season occupancy model is a linked two-level random effect model comprised of an ecological process (Equation 1) and observation model (Equation 2):
1. $Z_k \sim \text{Bernoulli}(\psi_{j,k})$
2. $y_{j,k} \sim \text{Bernoulli}(z_{j,kp_j})$

We modelled occupancy and detection with a Bernoulli distribution. We defined our survey length as one day. We considered three groups of covariates on occupancy: human modification variable (building density per km$^2$), landscape variables (core area largest patch index, latitude), and prey variables (cottontail detection per trap night and squirrel detections per trap night). We modeled scent lure during week 1, 2, 3, and 4 after the treatment was applied and the total proportion of connector landscape types as covariates on detection. We modelled single-season occupancy model in a hierarchical Bayesian framework run in software JAGS in R (Environmental Systems Research Institute 2014, R Core Team 2017). We ran the model with three parallel chains with 5,000 burn-in and 100,000 iterations. We assessed convergence using a r-hat value <1.1.

Results

From September to December 2019, we collected 503,225 images, recorded 37,106 detection events, and identified 22 mammalian species over the 25 sample areas. We recorded 1,469 human events and 2,642 domestic pet and livestock events.

We recorded 121 bobcat detections with an occupancy probability 0.561 (14 of 25 sites) and a detection rate of 0.040. Bobcat occupancy probability decreased when building density increased (estimated coefficient -32.127; 95% CI = -68.723 – -5.245) (Figure 2.2A) and as patches of core natural area increased (estimated coefficient 40.047 95% CI = -6.486 – 87.381) (Figure 2.2B). Occupancy probability of bobcats was highest in the northern region of Connecticut (estimated coefficient 17.753 95% CI = -3.613 – 51.420) (Figure 2.2E). As prey detection increased, bobcat occupancy probability decreased (cottontail estimated coefficient -
17.748 95%; CI = -47.931 – 12.061, squirrel estimated coefficient -18.747; 95% CI = -54.134 – 5.918) (Figure 2.2C, 2.2D).

Detection probability of bobcat decreased as the proportion of connector landscape types increased in relation to natural habitat in sample areas (estimated coefficient -0.946 95%; CI = -1.236 – -0.667) (Figure 2.3). Detection probability for bobcat was highest during the first week of scent lure (p = 0.055) with no difference between weeks (Table 2.1).

Discussion

Urbanization may negatively affect carnivores when development creates barriers to movement and isolates green spaces. We predicted that bobcat occupancy would be high in Connecticut due to the prevalence of exurban housing density (62.4% of developed lands). Here we show that bobcat occupancy is high within exurban landscapes and that bobcats occur in extremely suburban settings (944 buildings per km²). We also reveal that probability of bobcat occupancy decreases when building densities exceeds 700 buildings per km². We note that urban areas in Connecticut are smaller in size than the average bobcat home range, and thus bobcats that occur in urban areas may be traveling through and among suburban and exurban areas within their home range. Below we discuss how quantifying urbanization affected our understanding of how bobcats live in close proximity to people.

In Southern New England, we found that bobcats are thriving in landscapes that are forest intermixed with exurban development. We estimated bobcat occupancy probability of 0.56 across 0-1,250 buildings per km². Bobcat occupancy was high throughout rural, exurban, and mid-suburban developments, and then bobcat occupancy decreased above 700 buildings per km². We found that bobcats did not occupy urban building densities (>989 buildings/km²). Bobcats occupy areas with higher building density that we anticipated and our results differed from other
recent occupancy estimates in Raleigh, NC and Washington D.C. that found bobcats did not occupy urban housing densities (>1,000 housing units/ km²) (Parsons et al. 2018).

Natural areas, green spaces, and open areas become more limited in highly urbanized landscapes and the amount and configuration of these areas affect urban wildlife. For example, we were able to determine that bobcats maintained 100% occupancy after the core area largest patch index reached 10 on a scale from 0 to 100. This value corresponds to 0.1 km² core area patch size within a 1 km² area. Occupancy declined when a grid cell did not contain a patch of natural area of at least this size. Our landscape is primarily composed of exurban housing densities ranging from 7 to 123 buildings per km², and thus most bobcat home ranges in our region likely include areas with this level of housing. The 0.1 km² core area patch size is the minimum amount of core habitat needed for a bobcat to occupy a grid cell, and thus a bobcat may live or forage in this grid cell, or travel through a small patch of natural habitat while moving among areas of different housing densities. Throughout the entire study area of Connecticut only 20-grid cells, 1 km² in size, are greater than 1000 houses per km², and bobcats occupy the full range of housing densities from rural to high suburban, and thus bobcats can occupy 98.8% of the state.

Our study design with a three camera array within a 1km² sample area influenced how well various species are quantified with this dataset. The design was based on increasing bobcat detection and sampling a spatial scale relevant to bobcats, and thus this design hinders our ability to quantify other species using the same dataset. For example, we found that bobcat occupancy probability decreased as the two most common prey species detection per trap night increased in a sample area. One interpretation of this result is that bobcat occupancy does not track prey abundance and thus we found an example that contradicts previous literature (Anderson 1987;
Sandell 1989; Lovallo and Anderson 1996). However, we suggest an alternative interpretation that we cannot adequately quantify cottontails and squirrels with this dataset. For example, the best camera locations within the 1 km$^2$ sampling area for detecting bobcats is not the same locations that are best for detection of cottontails and squirrels. In urban places, cottontails use open areas such as backyard gardens near decks for cover, whereas bobcats travel along the edge of yards. Although we quantified a pattern, we suggest that further clarification is needed to describe how bobcats and prey species are using backyards and other urban features of the landscape.

Our results indicate in very high building densities, areas that have a low proportion of connector landscape types relative to natural area have a higher detection rate than areas with a high proportion of connector landscape types. Narrow, elongated patches of habitat are structural corridors (Vogt et al. 2009) created by the pressing of urbanization into remaining patches of green space. The elongated patches may also be functional corridors if animals follow elongated patches when traveling among large patches of habitat (Vogt et al. 2009). In this case, the corridors may act as funnels that cluster animals. We placed cameras in the only available green space and found that bobcat detection rates decreased as the proportion of connector landscape types increased such that the entire 1 km$^2$ sample area was connected. Natural areas became increasingly limited within sample areas with high housing densities, and structural corridors no longer spanned the entire 1 km$^2$ sample area. In these cases, small patches of core natural habitat were important predictors of occupancy and detection probability decreases in these areas. We suggest that bobcats are no longer living within (i.e., denning, breeding) the 1 km$^2$ sample area due to limited natural core habitat and are instead using the remaining natural areas as functional
corridors to move through. An ongoing tracking project will provide additional evidence to support that pattern described here.

Our previous understanding of how carnivores respond to urban development in the U.S. is based largely on quantifying humans using the U.S. Census data, and this data was the best available metric in the U.S. Here we provided an example of how this metric greatly influences our understanding of wildlife within urban development. The U.S. Census Bureau data is a social metric that is a count of housing units. Units of housing complexes (i.e., apartments) count individually towards the total housing units, and therefore can contain hundreds of units within a small surface area. The Microsoft Building Footprint layer, released in 2018 for the U.S., provides a spatial building footprint that includes houses, office buildings, evens sheds or outbuildings. Connecticut contains 1,521,123 (+/- 202) housing units but only 1,190,229 buildings. Our study design resulted in a similar pattern, where our sampling areas contained a greater number of housing units compared to the number of buildings (282 – 5,670 housing units per km², 0 – 1,250 buildings per km²). Though housing density and building density are positively correlated, we suggest that the U.S. Census data is a measure of human presence, whereas the Microsoft building layer is a direct measure of building density. This new clear distinction between housing units and building density will allow for a more complete understanding of wildlife within urban development. For example, we previously used a similar study design with random placement of 1 km² sampling areas but stratified with U.S. Census data up to 1,000 housing units expecting bobcat occupancy to have declined. We ended up with bobcat occupancy estimate of 0.89 with an estimate of 1.0 during the fall season (Chapter 1), and the new building layer confirmed that we were only sampling areas < 300 buildings per km² (Figure 2.4). We anticipate that additional urban wildlife research that can now describe
differences between housing density and human activities levels will soon resolve the current
dissidence that bobcat have colonized urban landscapes, yet are intolerant of human activity and
sensitive to urbanization (Crooks 2002; Riley 2006; Ordeñana et al. 2010).

As urbanization continues to spread globally and within the US, urban landscape
planning will become increasingly important to the wildland species now using these developed
landscapes. Additional research needs to be conducted to determine if species’ ability to occur in
urban landscapes is due to the fact that their home ranges are large enough to encompass a range
of wildland, exurban, and suburban housing densities. We observed bobcats occupying housing
density from rural to high suburban landscapes, though excluded from urban areas. Bobcats
require a level of core habitat in urban settings to persist in these landscapes, though the area
required may be minimal compared to surrounding rural areas. Bobcats once thought to be an
urban-sensitive species that could not coexist with people are demonstrating their ability to use
highly developed landscapes when not persecuted, following the pattern set by other
mesocarnivores species.
Literature Cited


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Tables & Figures

Table 2.1. Estimated detection probabilities for scent lure by week with 95% credible intervals.

<table>
<thead>
<tr>
<th>LURE</th>
<th>MEAN ESTIMATE</th>
<th>2.5% CI</th>
<th>97.5% CI</th>
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<td>0.050</td>
<td>0.078</td>
</tr>
<tr>
<td>SCENT WEEK 2</td>
<td>0.034</td>
<td>0.021</td>
<td>0.051</td>
</tr>
<tr>
<td>SCENT WEEK 3</td>
<td>0.046</td>
<td>0.030</td>
<td>0.068</td>
</tr>
<tr>
<td>SCENT WEEK 4</td>
<td>0.037</td>
<td>0.023</td>
<td>0.059</td>
</tr>
</tbody>
</table>
Figure 2.1. Sample area locations (2019) stratified using Microsoft Building Footprint layer. Note that although much of the state has 7 to 123 houses per km² (exurban), only 15% of the cells meet the definition of rural with less than 7 houses per km².
Figure 2.2 Estimated effect of building density (A), core area largest patch index (B), squirrel detection per trap night (C), cottontail detection per trap night (D), and latitude (E) on bobcat occupancy probability.
Figure 2.3 Estimated effect of proportion of connector landscape types on bobcat detection probability.
Figure 2.4 Comparison of sample areas stratified based on U.S. Census Data (A and B; Chapter 1) to sample sites stratified based on building density (C and D; Chapter 2). Census block in panel A is classified as 200-400 housing units per km² but the sampling area contained no buildings. Census block in panel B is classified at 800-10000 housing units per km² but the sampling area contained only 270 buildings. A similar number of buildings are found in panel B (270 buildings) and panel C (338 buildings) and these examples are in contrast to a sample area with so many buildings (967 buildings) that estimated bobcat occupancy was zero.
Chapter 3: Diet Estimates and Seasonal Variation in Bobcats (*Lynx rufus*) within an Intermixed Ecosystem

Abstract

Urban landscapes, generally thought to be risky to wildlife due to proximity to humans, can provide enticing food benefits in the form of trash, synanthropic species, domestic livestock and pets, or wildlife feeders such as bird feeders or bait piles. Connecticut ecosystem is intermixed forest and urban developments that contrasts wildland interfaiced urban landscapes in which bobcats forging ecology was previously studied. To understand how bobcat diet shifts among seasons and within and among housing densities, we analyzed bobcat hair collected from 2017 to 2019 across a range of housing densities for carbon and nitrogen stable isotope ratios to estimate diet. Using MixSIAR, we created a hierarchical mixing model in a Bayesian framework to correlate carbon and nitrogen isotope ratios of potential prey species to isotope ratios of bobcat hair. Herbivores comprised over 90% of bobcat diet and the Cottontail Group comprised more than 50% of bobcat diet, regardless of bobcat sex, housing density, or region within Connecticut. Male bobcats consumed more deer (13%) than females (11%), while both larger male and female bobcats consume more deer than smaller bobcats. Bobcats consumed more deer in suburban housing densities (22%) than exurban housing density (12%). Across season, the proportion of deer in bobcat diet decreased throughout seasons from spring to winter (7% to 4%). These results demonstrate that bobcats living within forest that is intermixed with exurban and suburban housing are able to maintain diets consisting of mostly natural prey.

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Chapter 3 prepared for journal submission with coauthor: Tracy Rittenhouse, Gideon Hartman, and Jason Hawley. Plural pronouns are used to represent the contributions of coauthors in preparation for future publication.
Introduction

Many carnivores once thought to not tolerate human disturbance are now thriving in urban environments (Wang et al. 2015) as evident by bobcats in the Texas metroplex (Young et al. 2019), coyotes in Chicago (Newsome et al. 2015), and cougars in Los Angeles (Riley et al. 2014). Urban landscapes are generally thought to be risky to wildlife due to the proximity to humans (Ditchkoff et al. 2006), yet these landscapes can provide enticing benefits such as shelter, refuge from predation, and food and water resources (Newsome et al. 2015). Wildlife are adapting to human disturbance, using man-made edges to stalk and hunt prey (Knopff et al. 2014) and exploiting abundant prey or anthropogenic food sources (Contesse et al. 2004; Newsome et al. 2010; Bateman and Fleming 2012; Merkle et al. 2013). Urban food resources come from a multitude of sources: urban gardens, compost, trash, synanthropic species, domestic livestock and pets, roadkill, and feeding of wildlife such as bird feeders or bait piles (Bateman and Fleming 2012).

Urban carnivore foraging ecology can change by capitalizing on the abundance of specific prey items. Urban landscapes provide suitable habitat for prey species such as raccoons, squirrels, rodents, and birds that benefit from food resources, refuge from predators, and generalized habitats (Ditchkoff et al. 2006; Randa and Yunger 2006; Bateman and Fleming 2012; Macdonald and Johnson 2015). These synanthropic prey species become very abundant, occurring at greater densities in urban areas than wildlands (McKinney 2006; Bateman and Fleming 2012), especially when species richness is reduced by urbanization (McKinney 2006, 2008). Furthermore, natural and alternative prey species in urban settings can lack anti-predator behaviors that rural prey display (Mccleery 2009) making urban prey easy to prey upon.
A foraging strategy that urban carnivores are using in human-dominated landscapes is widening the breadth of their diet, shifting diet habits to include anthropogenic resources. For example, cougars were considered to be specialized in herbivore prey, but now that cougars are using urban areas, their diets have become more generalized and include human-associated prey items (Moss et al. 2016). The shift in diet documented in cougars may be due to prey availability or prey size, since small synanthropic prey and domestic prey may require less handling time than wild prey (Prange and Gehrt 2004; Smith et al. 2016a). House cats also shift diet based on development, with cats in urban areas preying on smaller prey than cats in rural areas (Pearre and Maass 1998; Bateman and Fleming 2012). Foxes all over the world have been adapting to urban environment and exploiting anthropogenic food resources. More than half of the stomach contents of Swiss red foxes was anthropogenic (Contesse et al. 2004) and urban San Joaquin kit fox consumed food similar to humans, as shown in scat analysis (Newsome et al. 2010). Coyotes diets in Florida contained anthropogenic resources twice as often in suburban areas compared to wildlands (Grigione et al. 2011). Domestic animals can comprise a significant portion of diet in urban carnivore species. For example, domestic cats were found in 29% of coyote scat samples in San Diego and Orange counties, California (Larson et al. 2015) and 13.6% in coyotes’ scat in Malibu, CA (Shargo 1988). An emerging pattern from these studies is that food, as opposed to shelter, is the primary resource use that is changing in urban environments. Carnivores that are successful in adapting to urban environment are modifying their diet (Bateman and Fleming 2012) or supplementing their diet with anthropogenic resources (Newsome et al. 2015).

Bobcats are strict carnivores, therefore anthropogenic food sources such as garbage, compost and bird feeders are not a direct food source, unlike their urban competitors: coyotes, black bears, and foxes (Newsome et al. 2010; Morey et al. 2007). Bobcats prey on species
ranging in size from 0.7 to 5.5 kg, notably lagomorphs (Anderson and Lovallo 2003) and large rodents (Beasom and Moore 1977), yet other known prey include small rodents, birds, reptiles, domestic pets, and livestock (Hunter 2011). In northern regions, bobcats can prey on white-tailed deer (Litvaitis et al. 1984), depredating fawns and adult deer in poor health. Bobcats are known to consume native prey in both urban and rural environments (Knick 1990; Riley 1999; Fedriani et al. 2000). Bobcats in California were absent from the small urban fragments, and the diet in large fragments showed no anthropogenic food, and thus Larson et al. (2015) concluded that bobcats could not live in dense urban landscapes due to being unwilling to use anthropogenic food sources that coyotes and grey fox use readily. In New York, bobcats also consume wild prey and no anthropogenic food sources, but individual bobcats varied greatly in their diets (Warsen et al. 2014).

Bobcat feeding ecology in urban area warrants additional research (Riley 2010) because prey drive can affect bobcat habitat selection, home range size (Anderson and Lovallo 2003), and exposure to rodenticides (Riley 2010). The abundance and availability of prey species in urban areas may affect how or if bobcats occur in high housing density areas (Riley 2010). In northern California, bobcats found in urban areas rely more heavily on small mammals as a food source than rabbits and large rodents (Riley 2010). Prey switching is common behavior when the primary prey species declines in abundance (Bailey 1974; Leopold and Krausman 1986). To properly manage bobcats and the species they prey upon, bobcat feeding ecology and feeding habits across different housing densities must be better understood.

Estimating diet of individuals from a mammalian predator can be done using techniques such as scat samples, stomach content, predation sites, or stable isotope signatures from animal tissue. Kill sites, scat and stomach analysis take a snapshot in time of an individuals’ diet,
whereas hair and bone samples assimilate diet over time, from weeks to months, or seasons to years respectively (Roth and Hobson 2000). A comparison of scat and isotopic analysis of San Joaquin kit fox showed scat overestimated natural prey in their mostly anthropogenic diet (Newsome et al. 2010). In addition, kill sites overestimated large prey for larger prey because kill sites are not fully ingested whereas smaller prey items are (Smith et al. 2015; Kertson et al. 2011). The opposite occurs when estimating diet through stomach content. Small prey species are more easily identifiable because they are consumed whole or include large portions of the body. If stomach content is not processed thoroughly results may be biased towards easily identifiable species. Stable isotopes ratios give a diet estimate for an individual (Moss et al. 2016) and stable isotope analysis on hair samples is noninvasive technique to sample diet over a period of time longer than other methods.

We used stable isotope analysis to estimate the contribution of prey species in bobcat diet across the urban landscape in Connecticut. The urban landscape of Connecticut is an intermixed ecosystem that contrasts greatly to the urban landscapes where bobcat foraging ecology has previously been studied. Connecticut is a mosaic of primarily exurban housing densities, where urban development is intermixed with forest rather than interfaced (Bar-Massada et al. 2014). We hypothesize that the difference in prey availability (i.e., domestic and synanthropic species) between low and high development influence the prey consumed, and thus we expect to document a difference in carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope values in bobcats across housing densities. We expect that bobcats in rural-exurban housing densities will have a more varied diet than bobcats found in suburban-urban housing densities. In addition, we quantify differences in diet among individuals based on sex, region, and weight of bobcats and seasonality of male bobcats.
Methods

Connecticut has a unique mixture of development while also being predominately forest. Connecticut is the third smallest state covering 14,360 km² and comprised of four geographic regions: eastern uplands, western uplands, central river valley, and the coastal lowlands. Deciduous and coniferous forest cover over 50% of the state (UCONN Center for Land Use Education & Research 2015), primarily in the uplands, whereas the central river valley and coastal lowlands are comprised of densely urban areas (Ahearn 2004). Developed landscapes in Connecticut are dominated by exurban development (i.e., housing units between 7 and 123 per km²) that cover 64% of the state.

From 2017 to 2019, we collected hair samples from bobcats. Bobcat hair samples were collected from roadkill individuals and legally trapped bobcats by Connecticut Department of Energy and Environmental Protection (DEEP) and volunteer trappers for a movement study deploying GPS collars (unpublished). We pulled guard hairs from the backside of the neck. Bobcats undergo guard hair molt in late spring to early summer (Newsome et al. 2010; Maurel et al. 1986). Bobcats were trapped from September to February of 2018 and 2019, therefore the hair growth occurred for 3 to 7 months and represented diet from April to December. Roadkill bobcats were collected year-round; therefore, their diet reflected the period in which the animal was killed relative to the spring molt period. We analyzed 233 trapped and roadkill individuals (n= 133 M, 100 F) and 96 collared bobcats (n= 56 M, 40 F).

We collected hair from potential prey species from 2017 to 2019. Prey species considered were all species found at bobcat kill sites (2017-2018) identified by tracking study and stomach content of 70 roadkill bobcats necropsied by DEEP from 1986-2006. Prey included: two cottontail species, New England cottontail (NEC) (*Sylvilagus transitionalis*) and Eastern
cottontail (EC) \((Sylvilagus\ floridanus)\), Eastern grey squirrel \((Sciurus\ carolinensis)\), bird spp. \((Passerine)\), wild turkey \((Meleagris\ gallopavo)\), Canada goose \((Branta\ canadensis)\), muskrat \((Ondatra\ zibethicus)\), peromyscus, Eastern chipmunk \((Marmotini\ Tamias)\), white-tailed deer \((Odocoileus\ virginianus)\), raccoon \((Procyon\ lotor)\), duck spp. \((Anatidae)\), chicken \((Gallus\ gallus\ domesticus)\), woodchuck \((Marmota\ monax)\), Virginia opossum \((Didelphis\ virginiana)\), domestic cat \((Felis\ catus)\) (Table 3.1, Figure 3.1). We collected hair samples from prey found at bobcat kill sites, pulling hair from back of the neck when possible, and opportunistically found roadkill prey items. We processed and report the results from 5 individuals of each prey species.

Stable isotope preparation of prey and bobcat hair samples was completed in a University of Connecticut laboratory. We washed samples with 1.6 mL of 2:1 chloroform:methanol solvent in an Eppendorf reaction tube. We then vortexed the samples for an hour to remove lipids and contaminants, rinsed with miliQ water, and vortexed for an additional 30 seconds. This process was repeated 3 to 5 times. Samples were then dried at 40°C for at least 48 hours. For avian feathers, we removed the vane and treated them as hair. We pulverized each sample with scissors or with a mortar and pestle. Using an analytical balance (Mettler Toledo), we weighted between 500 and 1,000 μg of processed keratin sample into tin capsules (3.5 – 5mm).

Collared male bobcat hairs were sectioned for determining seasonal variation in isotope ratios \((N = 35\ adult\ males)\). After washing, we sectioned ~20-25 guard hairs in four 10 mm sections. We identified guard hairs from Hilton and Kutscha (1978) description of dorsal guard hairs: banded hair with brown/beige/black bands and are approximately 30-50mm in length. We cut from tip to root, the first section (tip) representing the oldest growth and the last section (root) the most recent growth. Guard hairs varied in length from 30-50mm, 35 individual bobcats were sectioned into four segments (10 mm). McLauren et al. (2015) showed that late season
(September – November) hair growth for wolves slowed; therefore, we decided that the first three segments could be approximately considered as early summer (April-May), middle summer (June-July), late summer (August-September), and the last section represented autumn-winter (October-December), but the precise growth season for bobcat guard hairs still remains unknown.

Samples were analyzed at the Boston University Stable Isotope Laboratory using a GeoVision Instruments IsoPrime isotope ratio mass spectrometer with an Eurovector elemental analyzer. Two standards were run, peptone (i.e. hydrolyzed animal protein) and glycine (i.e. citrus leaves). We report δ\textsubscript{13}C and δ\textsubscript{15}N values as parts per thousand (‰):

\begin{equation}
\delta X = \left\{ \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right\} \times 1,000
\end{equation}

where X is carbon or nitrogen and R is the ratio of \textsuperscript{13}C to \textsuperscript{12}C and \textsuperscript{15}N to \textsuperscript{14}N (Roth et al. 2007) (Error: \textsuperscript{13}C = 0.2 /₀₀₀₀, \textsuperscript{15}N=0.3 /₀₀₀₀). Captive bobcat (N = 3) with known diets (whole rodents and commercial carnivore food Toronto Feline Diet; N = 4 for each sample) were used to calculate a trophic discrimination factor between prey hair and bobcat hair (\Delta\textsuperscript{15}N mean = -3.359 SD = 1.073312, \Delta\textsuperscript{13}C mean = -3.4519, SD = 1.49365) (Carroll 2019).

SIBER, a package in R, uses standard ellipse area to describe niche breadth: the larger the area of the ellipse the higher diversity of sources in the consumer diet (Jackson et al. 2011). We used SIBER to calculate the standard ellipse area of bobcats across sex and across exurban-suburban developments. We used the maximum likelihood ellipses calculated using MCMC simulations in a Bayesian framework ran with 1,000,000 iterations, a burnin of 50,000 and thinned by 100.
To estimate the proportion of prey in bobcat diet, we calculated the proportion of each source (prey) in the diet of the consumer (bobcat) in a Bayesian framework using mixing models within the R package MixSIAR (Stock et al. 2018, R Core Team 2017). We collected 15 potential prey species ranging from herbivores to omnivores. We decided to remove muskrats due to their low presence in stomach content. We then grouped migratory avian species (Canada goose, duck spp., and bird spp.) and domestically fed species (domestic cats and chickens). We used hierarchical clusters analysis with Euclidean distance and Ward’s method to cluster the remaining species by their location multivariate isospace. Voles were an outlier group and thus removed. Some prey species have such similar diets (i.e. two herbivore species or two omnivore species) that the range of isotopic value overlapped, preventing us from being able to distinguish the species. The remaining species clustered into an omnivore group (turkey, mice, opossum, and raccoon), cottontail and woodchucks clustered together, chipmunk and squirrels clustered together, and finally deer was an isotopically distinguishable to species. Bobcat isotopic values were completely contained between the four groupings: deer, cottontail and woodchuck, squirrels and chipmunks, and omnivores (Table 3.1, Figure 3.2).

We classified housing groups using Theobald (2005) classifications as rural (0-6 houses per km²), exurban (7-123 houses per km²), suburban (124-988 houses per km²), and urban (>989 houses per km²). Collared bobcats in 2017 and early 2018 have a known home range and a known building density within its home range. None of the collared bobcats had a home range classified as rural or urban housing. Bobcats’ home ranges spanned exurban to suburban housing densities of 8-514 buildings per km². For bobcats collared in later 2018 and 2019, home range estimates have not been calculated and we used a placeholder housing density defined as a sex-
specific buffer relating to the median home range (F=19.4 km$^2$, M=54.7 km$^2$) around the trap location of the bobcats collared in year 2.

We ran three separate models that differed based on quality of data input in each model (full data model, collared bobcat model, and seasonal male model). We removed kittens from all models. For all models, we used uninformed priors and 3 chains of 3,000,000 iterations with a burin of 1,500,000 thinned by 500. The benefit to using MixSIAR is the inclusion of priors into the Bayesian mixing model. Priors are meant to constrain error around the mixing model. We chose to use uninformed priors due to extreme differences between the frequencies at which species were recorded in stomach content verses at kill sites. Although uninformed priors lead to large credible intervals, we suggest that the uniformed priors best represented our level of knowledge, especially the lack of information in highly urban areas.

The full model included data from collared, live trapped, and roadkill bobcats. The isotopic values from the sectioned hair of the collared males for seasonal analysis were averaged for this model and the collared bobcat model. We considered sex and mass as biological variables that would impact the proportion of prey in a bobcat’s diet. We categorized each individual into a region of the state: western uplands, eastern uplands, costal lowlands, and central river valley. We sampled bobcats in the four distinct regions of Connecticut: 30 bobcats in the coastal lowlands, 64 bobcats in the eastern uplands, 82 bobcats in the western uplands, and 57 bobcats in the central river valley. Posterior estimates were reported based on sex as a fixed effect and region as a fixed effect. The collared bobcat model included only adult bobcats that were collared. Posterior estimates were reported on sex as a fixed effect with mass as a categorical effect nested under sex and housing density as a fixed effect. The average mass of a male bobcat captured was 12 kg and female weight was 9 kg. Mass was categorized into two
groups: lighter or heavier than the average male or female capture. The seasonal male model included the adult male bobcats that had four full sections of hair sampled. The posterior estimate that was reported was season as a fixed effect.

**Results**

Female bobcats had an average $\delta^{13}\text{C}$ ratio of -21.99‰ and $\delta^{15}\text{N}$ ratio of 6.55‰ isotopic value, whereas the isotopic values for male bobcats was $\delta^{13}\text{C}$ ratio of -22.12‰ and $\delta^{15}\text{N}$ ratio of 6.72‰. Bobcats living in exurban housing category had lower average $\delta^{13}\text{C}$ ratio of -22.00‰ and $\delta^{15}\text{N}$ ratio of 6.52‰ than bobcats in suburban housing category ($\delta^{13}\text{C}$ ratio of -22.41‰, $\delta^{15}\text{N}$ ratio of 6.79‰).

Using standard ellipse area, female bobcats generally had a wider dietary niche (2.76) than male bobcats (2.07) (Figure 3.3A, 3.4A). Small bobcats had the widest dietary niche ($M = 1.9, F = 1.9$) (Figure 3.3E, 3.4E). Dietary breadth was similar among regions (western 2.07, valley 1.58, eastern 2.32), yet the lowest diet breadth was in the coastal lowlands (1.3) (Figure 3.3B, 3.4B). Bobcats in areas of exurban housing have a wider dietary niche (2.0) than in suburban housing (1.2) (Figure 3.3C, 3.4C). The largest standard ellipse area among seasons was fall-winter (2.6), while all other seasons remain similar in size (Figure 3.3D, 3.4D, Table 2).

We were not able to distinguish the isotopic signatures of eastern cottontail, New England cottontail, and woodchucks and we thus refer to these three species together as Cottontail Group. Grey squirrels and eastern chipmunk were also indistinguishable, and we refer to those two species as Squirrel Group. Cottontail Group comprised the majority of bobcat diet (>50%) regardless of sex, weight, housing density, and season with the exception occurring in regions. Cottontail Group made up most of the diet in western uplands and coastal lowlands (Figure 3.5B,D). In the eastern uplands and central valley Cottontail Group were second to deer in
bobcat diet (Figure 3.5A,C). The remainder of the diet shifted in the proportions of deer and Squirrel Group varied among the variables. Male bobcats had a higher proportion of deer (13%) while females had a higher proportion of Squirrel Group in their diet (27%) (Figure 3.6, Table 3.3). Large male and female bobcats had a higher proportion of deer (23%, 20%, respectively) while small male and female bobcats had a higher proportion of Squirrel Group in their diet (28%, 27%, respectively) (Figure 3.7, Table 3.3). Deer made up the majority of bobcat diet in the eastern uplands (40%) and central valley (42%), and only 8% in the western uplands (Figure 3.5). Squirrel Group were more abundant in bobcat diet in both upland regions and low elevation areas in the central valley and the coastal lowlands (Figure 3.5). Squirrel Group were also more prevalent than deer in exurban housing, while in suburban housing deer was a greater proportion of the diet than Squirrel Group (Figure 3.8). Deer decreased in proportion of diet across seasons, while Squirrel Group increased from midsummer to late summer (Figure 3.9). Our Omnivore Group comprised less than 5% of bobcat diet (Table 3).

**Discussion**

As urban carnivores use more developed areas, monitoring and reconstructing their feeding habits across a range of urban environments is important for understanding potential human-wildlife conflict issues, monitoring prey species of concern, and determining general health of the population. Throughout a mosaic of housing densities, bobcats in this study did not incorporate anthropogenic food sources into their diet. We found little evidence of bobcats consuming domestic animals. Furthermore, our results confirmed our expectation that bobcats in rural-exurban housing densities have a more varied diet than bobcats in suburban-urban housing densities. Here we discuss differences in bobcat diet across biological traits (sex, weight), landscapes (regions, building density), and season.
Domestic prey and synanthropic species can be important sources for strict carnivores (Smith et al. 2016a); however, domestic animals comprised a negligible proportion of the diet of bobcats that we sampled. Throughout the mosaic of housing densities, bobcats are surviving on native prey species and not supplementing their diet with domestic animals. Other carnivore species in urban environments are taking advantage of high density of domestic pets and their lack of anti-predator behaviors (McCleery 2009). Domestic animals’ isotopic values were significantly different from those of bobcats, making them an unlikely significant source in bobcat diet, if any. Our study shows that bobcats can live in human-dominated landscapes by preying on native species within these landscapes. Our results confirm the prey that bobcats regularly consume but cannot rule out the possibility that bobcats may depredate an animal that is not consumed. Conflicts that can arise when wild animals prey on domestic animals are not the result of bobcats shifting prey when in urban areas.

Herbivores (i.e., deer, cottontail, woodchuck, squirrel, and chipmunk) comprised over 90% of bobcat diet while the Omnivore Group (i.e., raccoon, opossum, rodents, and wild turkey) made up less than 5% of the diet. Prey size and risk associated with depredating a species may influence the proportion of species in bobcats’ diet. Although rodents can be found in high densities in developed areas (Bateman and Fleming 2012), our results suggest that large prey species, such as deer and cottontails, are more profitable prey species for exurban bobcats. In California, the second highest cause of death to coyotes was anticoagulant rodenticide toxicity (Riley et al. 2003) and bobcat with high levels of toxicity developed notoedric mange (Riley et al. 2007). We found that the high abundance of deer, cottontail, and squirrel in bobcat diet may reduce bobcat consumption of small mammals and exposure to rodenticide toxicity that is a concern to bobcat health. Raccoons, opossums, and turkey are likely high risk species due to the
potential risk of injury in pursuit which may limit how often bobcats target these species (Spears et al. 2003; Mukherjee and Heithaus 2013). Cottontail consistently comprised more than 50% of bobcat diet, regardless of sex, housing density, or region. Although we could not distinguish New England cottontail, eastern cottontail, and woodchuck via isotopic signatures, we suggest that bobcats are primarily eating the two cottontail species. Woodchucks hibernate, yet there was no decrease in the signature during the winter. Furthermore, woodchuck was only reported in stomach dissection 4 times (1986-2017) and at 29 out of 444 bobcat kill sites (2017-2020) (unpublished data, DEEP).

Bobcat dietary breathe and proportion of prey varied across housing densities. Exurban developments have a wider variety of prey species (McKinney 2006), whereas higher housing decreases species richness and increases abundance (McKinney 2006, 2008). We revealed a similar pattern in bobcat diets, as diets spanned a wider spread of carbon and nitrogen ratios in exurban housing than suburban housing. When plotted by housing density, we found that the proportion of Squirrel Group opposed the proportion of deer (Figure 3.8). Squirrels are more associated with trees and low density developments (Benson 2013) and we found the Squirrel Group in higher proportion in diet of bobcats with exurban home ranges and decrease in suburban bobcats. We found deer in higher proportion in suburban bobcat diet compared to exurban diet. Deer thrive in heavily human-dominated landscapes (Foster et al. 2002). One possible explanation is that suburban landscapes may not provide the necessary cover for deer to escape from bobcat predation, and thus bobcat may be drawn to hunt in these areas or are more successful at depredating deer in suburban areas. Alternatively, deer may be injured by cars more frequently in urban areas and thus more vulnerable to predation.
We found that proportion of prey species in bobcat diet differed regionally. Bobcats are habitat generalists (Hansen 2007) and span the rural-urban housing densities throughout all regions of Connecticut (Chapter 1-2). While all three groupings of herbivore prey are, to varying degrees tolerant of urbanizations, their habitat requirement in urban settings vary and may influence the extent to which bobcat target a species prey type. Highly urbanized landscapes lack the canopy structure the Squirrel Group needs to persist. Bobcats in the densely human populated central river valley region had less squirrels in their diet, whereas, squirrel was a large proportion of bobcat diets in the forested upland regions. Deer exhibit the opposite pattern. Deer are the largest prey source consumed in the central valley followed close by the Cottontail Group, as both deer and cottontail thrive in areas heavily used by humans (Foster et al. 2002). The western and eastern uplands are separated by the central river valley and the proportion of Cottontail Group and deer in the diet are vastly different between the two regions. In the eastern uplands, the proportion of deer is 40% and cottontail is 23%, whereas in the western uplands Cottontail Group make up 50% while deer comprised only 8% (Figure 3.5).

New England Cottontails are the native lagomorph species throughout New England. Due to forest maturation and urbanization, New England cottontail have experienced drastic population declines across all New England (Fuller and Tur 2012). In New Hampshire, a stable isotope analysis of historic (1950-1960) and contemporary bobcats revealed that bobcat diets have shifted from a lagomorph-specialized diet to a more generalist diet (Carroll 2019). Bobcat isotopic values from Connecticut aligned more closely with those of historic bobcats from in New Hampshire and Vermont. The range of the nonnative lagomorph species, eastern cottontail, has expanded eastward throughout southern New England and eastern cottontail are now abundant, especially within development where eastern cottontail live in backyard gardens while
New England cottontail does not. Bobcats in Connecticut have not experienced a drastic shift away from lagomorphs over time as documented in the northern New England (Carroll, 2019), suggesting bobcat prey upon both eastern cottontail and New England cottontail in southern New England. Bobcat expansion into urbanized areas in New England may be supported by increase in eastern cottontail. As conservation efforts are currently focused on New England cottontail, future research that confirms that woodchucks are not a common prey item and methods that can distinguish New England cottontail and eastern cottontail would be important to informing New England cottontail conservation efforts.

Seasonal difference in the proportion of prey found in bobcat diet align with our previous understanding of bobcat foraging ecology. Fawning season for deer in the northeast is in May and June, and we detected an increase in proportion of deer in bobcat diet in early to midsummer. Deer was always present in the diet throughout the year, yet the amount of deer decreased to the lowest proportion occurring in the fall-winter as fawns approach adult size. Furthermore, we documented that the proportion of Squirrel Group in bobcat diet increases relative to deer. Cottontail Group make up more than 70% of bobcats’ diet across all seasons.

Bobcat diet consisted primarily of native prey species in natural habitats, throughout backyards, and developed landscapes. The ability of bobcats to persist on native prey species across different landscapes is key to their success. As we demonstrated bobcats in developed areas are not exhibiting prey switching behaviors between native and domestic prey species which may limit the potential of human-wildlife conflict issues to arise.
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Maurel D., Coutant C., Boissin-Agasse L., & Boissin J. (1986). Seasonal moulting patterns in three fur bearing mammals: The European badger (Meles Meles L.), the red fox (Vulpes vulpes L.), and the mink (Mustela vison). A morphological and histological study. Can J Zoo, 64, 1757–1764. 10.1139/z86-265


Riley, SPD (1999) Spatial organization, food habits and disease ecology of bobcats (Lynx rufus) and gray foxes (Urocyon cinereoargenteus) in national park areas in urban and rural Marin County, California. Ph.D. dissertation. University of California, Davis


### Tables & Figures

Table 3.1. Potential bobcat prey species sample, and groupings based on isotopic values. Groupings included in the model*

<table>
<thead>
<tr>
<th>Species</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>New England Cottontail (<em>Sylvilagus transitionalis</em>)</td>
<td></td>
</tr>
<tr>
<td>Eastern Cottontail (<em>Sylvilagus floridanus</em>)</td>
<td>Cottontail Group*</td>
</tr>
<tr>
<td>Woodchuck (<em>Marmota monax</em>)</td>
<td></td>
</tr>
<tr>
<td>Eastern Grey Squirrel (<em>Sciurus carolinensis</em>)</td>
<td>Squirrel Group*</td>
</tr>
<tr>
<td>Eastern Chipmunk (<em>Marmotini Tamias</em>)</td>
<td></td>
</tr>
<tr>
<td>Raccoon (<em>Procyon lotor</em>)</td>
<td></td>
</tr>
<tr>
<td>Virginia Opossum (<em>Didelphis virginiana</em>)</td>
<td>Omnivore Group*</td>
</tr>
<tr>
<td>Mice (<em>Peromyscus</em>)</td>
<td></td>
</tr>
<tr>
<td>Wild Turkey (<em>Meleagris gallopavo</em>)</td>
<td></td>
</tr>
<tr>
<td>White-tailed Deer (<em>Odocoileus virginianus</em>)</td>
<td>Deer*</td>
</tr>
<tr>
<td>Vole (<em>Microtus</em>)</td>
<td>Vole</td>
</tr>
<tr>
<td>Muskrat (<em>Ondatra zibethicus</em>)</td>
<td>Muskrat</td>
</tr>
<tr>
<td>Bird spp. (<em>Passerine</em>)</td>
<td></td>
</tr>
<tr>
<td>Canada Goose (<em>Branta canadensis</em>)</td>
<td>Migratory Group</td>
</tr>
<tr>
<td>Duck spp. (<em>Anatidae</em>)</td>
<td></td>
</tr>
<tr>
<td>Domestic Cat (<em>Felis catus</em>)</td>
<td>Domestically Feed Group</td>
</tr>
<tr>
<td>Domestic Chicken (<em>Gallus gallus domesticus</em>)</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.2. Mean estimates with 95% credible intervals for standardized ellipse area.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean Estimates</th>
<th>2.5% CI</th>
<th>97.5% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>2.78</td>
<td>2.28</td>
<td>3.39</td>
</tr>
<tr>
<td>Male</td>
<td>2.08</td>
<td>1.75</td>
<td>2.46</td>
</tr>
<tr>
<td>Large Male</td>
<td>1.26</td>
<td>0.89</td>
<td>1.89</td>
</tr>
<tr>
<td>Large Female</td>
<td>1.18</td>
<td>0.70</td>
<td>2.01</td>
</tr>
<tr>
<td>Small Male</td>
<td>1.90</td>
<td>1.30</td>
<td>2.84</td>
</tr>
<tr>
<td>Small Female</td>
<td>1.93</td>
<td>1.28</td>
<td>2.93</td>
</tr>
<tr>
<td>Western</td>
<td>2.07</td>
<td>1.68</td>
<td>2.59</td>
</tr>
<tr>
<td>Valley</td>
<td>1.58</td>
<td>1.24</td>
<td>2.10</td>
</tr>
<tr>
<td>Eastern</td>
<td>2.32</td>
<td>1.78</td>
<td>2.93</td>
</tr>
<tr>
<td>Coastal</td>
<td>1.30</td>
<td>0.91</td>
<td>1.90</td>
</tr>
<tr>
<td>Exurban</td>
<td>1.98</td>
<td>1.57</td>
<td>2.52</td>
</tr>
<tr>
<td>Suburban</td>
<td>1.23</td>
<td>0.84</td>
<td>1.90</td>
</tr>
<tr>
<td>Early Summer</td>
<td>1.75</td>
<td>1.24</td>
<td>2.46</td>
</tr>
<tr>
<td>Midsummer</td>
<td>1.83</td>
<td>1.33</td>
<td>2.62</td>
</tr>
<tr>
<td>Late Summer</td>
<td>1.86</td>
<td>1.34</td>
<td>2.65</td>
</tr>
<tr>
<td>Fall-winter</td>
<td>2.64</td>
<td>1.89</td>
<td>3.72</td>
</tr>
</tbody>
</table>
Table 3.3. Prey grouping proportion (%) of bobcat diet for all model, collared model, and season models from mixing models.

<table>
<thead>
<tr>
<th></th>
<th>Squirrel Group</th>
<th>Deer</th>
<th>Omnivore Group</th>
<th>Cottontail Group</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sex</strong></td>
<td>Male</td>
<td>20.5 ± 8.8</td>
<td>13.1 ± 10.7</td>
<td>5.1 ± 4.7</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>27 ± 9.2</td>
<td>10.2 ± 8.2</td>
<td>4.0 ± 3.5</td>
</tr>
<tr>
<td><strong>Region</strong></td>
<td>Eastern uplands</td>
<td>31.4 ± 10.4</td>
<td>40.1 ± 17.6</td>
<td>5.5 ± 7.9</td>
</tr>
<tr>
<td></td>
<td>Western uplands</td>
<td>36.0 ± 7.3</td>
<td>8.6 ± 5.1</td>
<td>1.8 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>Central river valley</td>
<td>14.3 ± 6.5</td>
<td>42.4 ± 10</td>
<td>3.6 ± 3.9</td>
</tr>
<tr>
<td></td>
<td>Coastal lowlands</td>
<td>18.6 ± 6.9</td>
<td>29.5 ± 10.9</td>
<td>3.3 ± 3.5</td>
</tr>
</tbody>
</table>

| **Sex-Weight**        |                |      |                |                  |
|                       | Small females  | 27.0 ± 11 | 11.2 ± 7.9 | 3.6 ± 3.2 | 58.1 ± 13.5 |
|                       | Large females  | 18.9 ± 9.2 | 19.6 ± 12.5 | 3.8 ± 4 | 57.6 ± 14.4 |
|                       | Small Males    | 27.9 ± 11 | 8.4 ± 7.7 | 2.0 ± 2.5 | 61.6 ± 13.5 |
|                       | Large Males    | 12.1 ± 7.8 | 23.2 ± 15.3 | 4.9 ± 5.7 | 59.8 ± 15.1 |
| **Housing**           | Exurban        | 28.8 ± 8.8 | 11.7 ± 7.8 | 3.6 ± 3.1 | 55.9 ± 11  |
|                       | Suburban       | 17.1 ± 7.7 | 22.3 ± 12 | 3.8 ± 3.9 | 56.8 ± 12.2 |

| **Season**            |                |      |                |                  |
|                       | Early Summer   | 13.8 ± 10.1 | 7.1 ± 6.2 | 3.2 ± 2.9 | 75.9 ± 12.1 |
|                       | Midsummer      | 13.8 ± 11.1 | 6.7 ± 6.7 | 3.0 ± 3.3 | 76.4 ± 13.3 |
|                       | Late Summer    | 16.9 ± 12 | 6.2 ± 4.1 | 3.5 ± 3.7 | 73.4 ± 13.8 |
|                       | Fall-winter    | 15.7 ± 13 | 4.1 ± 4.8 | 3.1 ± 3.7 | 77 ± 14.2 |
Figure 3.1. Mean and standard error isotopic values of potential prey species. Small black dots are isotopic values of bobcats.
Figure 3.2. Mean and standard error isotopic values of four prey groupings. Small black dots are isotopic values of bobcats.
Figure 3.3. Maximum likelihood standardized ellipse for bobcat carbon and nitrogen isotopic values by A) sex, B) region, C) housing, D) season, and E) sex-weight.
Figure 3.4. Maximum likelihood standardized ellipse area for bobcat carbon and nitrogen isotopic values by A) sex, B) region, C) housing, D) season, and E) sex-weight.
Figure 3.5. Posterior distributions generated from stable isotope mixing models for bobcats in the A) western uplands, B) eastern uplands, C) coastal lowlands, and D) central river valley of Connecticut.
Figure 3.6. Posterior distributions generated from stable isotope mixing models for A) male and B) female bobcats in Connecticut.
Figure 3.7. Posterior distributions generated from stable isotope mixing models for A) small male, B) large male, C) small female, and D) large female bobcats in Connecticut.
Figure 3.8. Posterior distributions generated from stable isotope mixing models for bobcats with home ranges classified as A) exurban and B) suburban in Connecticut.
Figure 3.9. Posterior distributions generated from stable isotope mixing models for male bobcats in the A) early summer season, B) midsummer season, C) late summer season, and D) fall-winter season in Connecticut.
Conclusion

As a top predator in New England, I found bobcats are thriving in landscapes that are forest intermixed with exurban development, even in highly suburban neighborhoods (500-850 buildings per km\(^2\)) by persisting on a diet consisting of cottontails, deer, and squirrels. Yet, to maintain this wide-ranging carnivore in this human-dominated landscape requires a minimum amount of core natural area in developed landscapes to allow for foraging and movements throughout a bobcat home range. For example, I estimated bobcats only occupied a 1 km\(^2\) grid cell if that grid cell contained at least 0.1 km\(^2\) of core natural area. Further research is needed to articulate how this minimum value may change when the grid cell is imbedded within landscapes of differing extents of development. Because in Connecticut, most suburban neighborhoods are smaller than a bobcat home range, bobcats living in suburban neighborhoods also frequent exurban neighborhoods. Yet, my results confirm that bobcats have the ability to live within 98% of the neighborhoods in Connecticut, and thus likely much of the eastern United States.

Urban landscapes may be enticing to bobcats, but high human activity can be detrimental to their success. Bobcat monitoring should focus on identifying if the following potentially detrimental things warrant management actions. For example, bobcats and mountain lions in California are experiencing high levels of rodenticide toxicity when switching prey species to rodents in urban developments and, as a result, are dying or developing diseases such as mange (Riley et al. 2007). We found no evidence that bobcats were exhibiting prey switch behaviors to rodent prey in urban environments and thus toxicity poisoning may not currently be a concern throughout New England. Second, high density of roads can represent a significant source of bobcat mortality due to vehicle collisions in urban landscapes (Tigas et al. 2002). In the last decade, reports of roadkill bobcats have been increasing (unpublished data, DEEP). This project included increased effort in recovering reported road killed bobcats in Connecticut, which
resulted in more than 201 bobcats recovered from 2017 to 2019. Yet in many instances carcasses would be missing by the time I arrived, suggesting that citizens are illegally collecting carcasses from the roadside. The total amount of bobcat road mortality is thus still not well understood. As these wide-ranging carnivores persist in and move through urban developments dominated by high traffic roads, creating safe wildlife crossings (i.e., wildlife overpasses and underpasses) may be important to their success in these landscapes. Third, the high abundance of stray and domestic pets in urban areas may lead to an increase in human-wildlife conflict, such as predation of pets or disease transmission. We found that house cats were not commonly captured on cameras in exurban neighborhoods but increased in suburban neighborhoods (> 700 houses per km²). Coyotes and mountain lions are known to supplement their natural diet in urban areas with domestic cats (Larson et al. 2015; Smith et al. 2016b) and in Florida, mountain lions are contracting feline leukemia virus from domestic cats (Brown et al. 2008). We found no evidence that bobcats incorporate domestic animals (i.e., chickens, stray cats) into their diet in this region. Further research could explore behavioral interactions among house cats and bobcats in suburban neighborhoods. My research suggests that bobcats are benefiting from the expansion of the non-native eastern cottontails and thus further research is needed to distinguish the amount of predation on eastern cottontails versus the native, rare New England cottontail.

The current presence of bobcats within suburban neighborhoods is an indicator that humans and predators can co-exist. These urban carnivores are charismatic and gather attention from the public and wildlife managers. Wildlife management has changed from a discipline focused on management of wildlife within wildland to wildlife within cities. This change will continue as urbanization continues globally. Increased collaborations between wildlife managers
and urban planners will likely be foundational to designing landscapes that continue to allow for the co-existence of both people and wildlife into the future.
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