Impacts of Artificial Light at Night on Space Use and Trophic Dynamics of Urban Riparian Mammals in Columbus, Ohio

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By

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The Ohio State University

2022

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Abstract

Artificial light at night (ALAN) is a growing environmental stressor due to human expansion and increased urbanization. ALAN has shown to have significant impacts on a suite of taxa and on multiple levels of biological organization, but most research has focused on individual to population levels of biological organization. Furthermore, there has been a disproportionate research emphasis on terrestrial vs. aquatic ecosystems. In this study, I investigated the impacts of ALAN on riparian mammal space use and food webs along 12 small streams in Columbus, Ohio, USA. Seasonality and time of day were the strongest drivers of mammal community composition along streams, despite the presence of ALAN. Seasonality, sediment size, and other site-level differences, but not ALAN, were associated with total mammal space use and species richness. No species-specific small mammal captures or species/guild-specific camera-trap encounters were impacted by ALAN. In the context of this study, sediment size is likely a proxy for either stream size or urbanization but also a potentially important structural factor related to small-mammal movement across streams.

ALAN presence was related to the proportion of energy derived from aquatic vs. terrestrial primary producer pathways in the genus *Peromyscus*, the only small mammals with sufficient sample size to estimate diet proportions. At illuminated reaches, *Peromyscus* nutritional subsidies derived from aquatic primary producer pathways (i.e., originating from stream periphyton) were 1.2% lower at lit compared to unlit reaches. Canopy cover was also associated with the proportion of energy derived from the terrestrial primary producer pathway that is indirectly consumed by *Peromyscus* (i.e., originating from aquatic detritus). Site – as a random effect in linear-mixed models – explained the greatest amount of variation in the proportion of energy derived from different primary producer pathways.

Overall, I did not find evidence that ALAN was associated with mammal space use or community composition in the riparian areas that I studied, but I did find evidence that ALAN was related to trophic interactions of small mammals and the type of energy sources they consumed. However, changes in energy subsidies were small and may not be ecologically consequential. These results can be used in conjunction with the Ohio Department of Transportation (ODOT) to establish potential roadway lighting thresholds to minimize lighting impacts on mammals that use riparian areas in urban centers. Current lighting levels (>3.5 lux) could be used as a threshold to prevent mammal habitat use impacts by ALAN. Further studies should experimentally increase light intensity and area of ALAN infiltration around streams, considering the home range sizes of mammals, to better understand possible ALAN impacts on mammal habitat use and food web interactions.

Acknowledgments

I would like to thank Ari Yamaguchi, Stephanie Li, Delaney Kelch, Justin Gillian, and Lars Meyer and other member of the Stream and River Ecology (STRIVE) Lab for their help with both field and lab work. I would also like to thank Dr. Jason Bohenek his statistical assistance. I would like to thank my parents, Mike and Coleen Gilboy, for supporting me to reach my goals and encouraging me to never give up. Finally, I would like to thank my committee members (Dr. Robert Gates and Dr. Stanley Gehrt) and my advisor, Dr. Mažeika Sullivan, for their knowledge, guidance, and patience as they assisted me in completing this thesis. Funding support was provided by ODOT (Ohio Department of Transportation) GRT-00052122 (to Dr. Mažeika Sullivan) and The Ohio State University (to Michael Gilboy and Dr. Mažeika Sullivan).

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Chapter 1: Background and Literature Review

Introduction

Artificial light at night (ALAN) is an environmental stressor caused by light pollution (Rich and Longcore 2013). Also referred to as ecological light pollution (Longcore and Rich 2004), ALAN is a growing ecological problem that will increase in intensity and extent as people increasingly urbanize the planet. ALAN is already a global problem, with astronomical light pollution extending to every inhabited continent (Elvidge et al. 1997, Cinzano et al. 2001). Even though ALAN is such a wide-ranging issue, many of the impacts and underlying mechanisms of ALAN are poorly understood.

ALAN can impact ecological processes from the individual to the ecosystem level, although most studies have focused on individuals and populations (Bishop 1969, Russart et al. 2018, Sanders and Gaston 2018, Zapata et al. 2019). ALAN has been shown to change wildlife interspecific interactions (Rotics et al. 2011), food-web interactions (Sullivan et al. 2019, Zapata et al. 2019), movement patterns (Rotics et al. 2011, Bliss-Ketchum et al. 2016), reproduction (Touzot et al. 2020), foraging (Da Silva et al. 2017), and physiology (Schoech et al. 2013, Le Tallec et al. 2016, Zhang et al. 2019). Many studies on ALAN impacts have focused on birds and herpetofauna (i.e., Rodríguez et al. 2013, Weishampel et al. 2016, Da Silva et al. 2017, Touzot et al. 2020), but few have studied mammals. Most mammal studies have focused on bats (reviewed in Stone et al. 2015).

Like most wildlife, urbanization has strongly influenced terrestrial mammal communities (McKinney 2002). Mammals have been pushed out of native habitats by construction of buildings and impervious surfaces, leading them to rely on green spaces for movement and persistence in an urban area (Gallo et al. 2017). Riparian areas are an important green space for mammals in urban areas. Riparian forests around streams and rivers provide cover, nutritional resources, and corridors for movement for urban-dwelling mammals (Hilty and Merenlender 2004, Mahan and O’Connell 2005). Riparian forests have complex food webs that involve terrestrial energy sources contributing to the aquatic consumers through inputs of terrestrial plant material and invertebrates (Vannote et al. 1980) and aquatic energy sources contributing to terrestrial consumers through emergent insects that have larval life stages in the water and emerge as adults (Kautza and Sullivan 2016). Increases in urban lighting could lead to greater

ALAN exposure in these riparian zones, with unknown impacts on species movement, community composition, and food web interactions.

Astronomical and Ecological Light Pollution

Urbanization and human expansion impacts wildlife through habitat fragmentation, reduction or removal of keystone species, and reduction of biodiversity through urban homogenization (McKinney 2002, 2006). ALAN is a growing issue that contributed to ecosystem degradation from urbanization. Artificial light pollution is one of the fastest increasing forms of environmental degradation, with ALAN intensity exponentially greater than natural nighttime light produced by moonlight and starlight (Falchi et al. 2011).

Much of this growth is happening in the tropics, where urban growth and industrial expansion has occurred more recently than in temperate locations. For example, Salvador, Brazil, grew from a population of 403,000 in 1950 to over 3,000,000 in 2000, leading to massive urban sprawl accompanied by an increase in ALAN (Utzinger and Keiser 2006). Since the tropics have minimal seasonal variation in patterns of light and dark, tropical species are more adapted to consistent diel patterns. This means that tropical species may be more sensitive to ALAN than extratropical species since it can alter the natural diel (Gliwicz 1999).

Temperate species, while adapted to greater seasonal shifts in diel patterns, are still sensitive to ALAN. This is important because ALAN is a more widespread issue in temperate regions due to a longer history of urbanization, leading to more land area being developed by humans (McDonald et al. 2013). In 2001, it was estimated that 90% of the United States and United Kingdom had elevated nighttime light levels, with several other European nations above 80% (Cinzano et al. 2001). Those percentages have increased globally in the last 20 years, meaning that species living in these highly industrialized nations have a high likelihood of encountering ALAN (Figure 1.1). With such a rapid increase in this environmental disturbance, a greater catalog of information on the impacts of ALAN is needed.

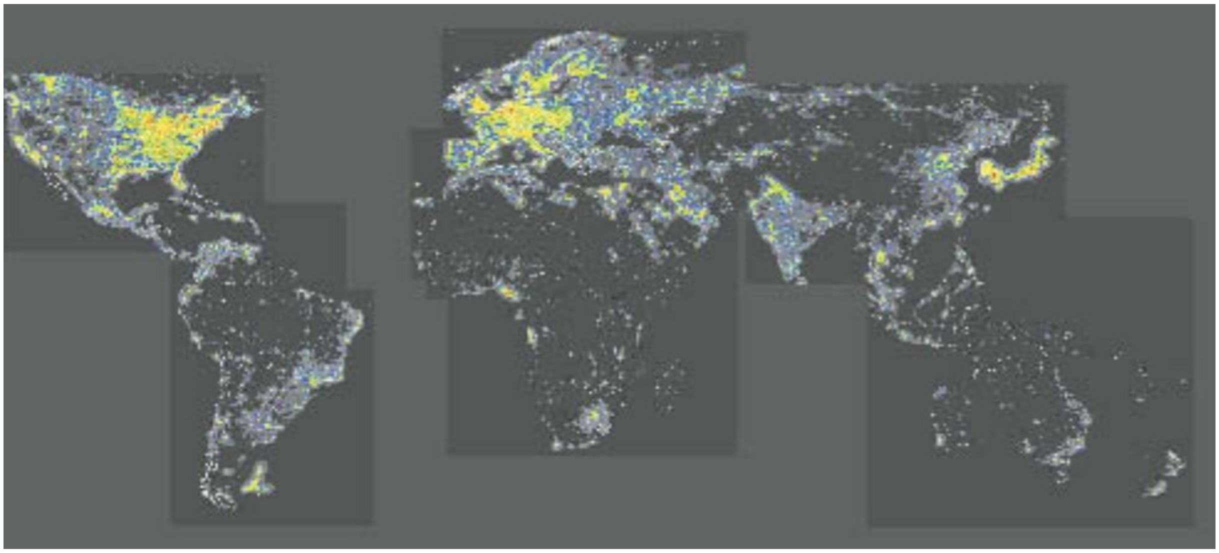

Figure 1.1: The first artificial night sky brightness atlas, originally presented by Cinzano et al. 2001. Yellows, reds, and whites represent brighter night skies from artificial light while blacks and greens represent darker skies.

The intensity of light, or lux, is not the only component of ALAN that is environmentally detrimental. The different spectral range of artificial light sources have impacted reproduction (Witherington 1992), foraging behavior (Hunt et al. 2001), and navigation (Bennett and Cuthill 1994) in different taxa. While these impacts are minimized when light sources that emit a narrower spectrum of wavelengths such as low-pressure sodium (LPS) and high-pressure sodium (HPS) lamps (Witherington 1992), the current shift to lights with "whiter" light and a wider emittance spectrum such as light emitting diode (LED) bulbs (Elvidge et al. 2010) means that impacts from the spectral composition of light are predicted to grow (Gaston et al. 2012).

Light pollution can be broken down into two main divisions: astronomical light pollution and ecological light pollution. Astronomical light pollution is when celestial bodies are washed out from light that is directed or reflected, a phenomenon that occurs from many light sources and results in sky glow (Longcore and Rich 2004). Astronomical light pollution impacts astronomical observations by creating sky glow, creating a barrier for light collecting telescopes (Riegel 1973) and is visible from satellite imagery (Figure 1.1). Ecological light pollution occurs when artificial light changes the natural temporal patterns of light and dark periods . Originally called “photopollution” (Verheijen 1985), ecological light pollution can happen from direct light exposure, prolonged increased lighting, and unusual fluctuations in the light pattern. Ecological light pollution can be caused directly by light sources such as streetlights, stadium lights, and housing/business lights as well as indirectly through reflected sky glow (Longcore and Rich 2004).

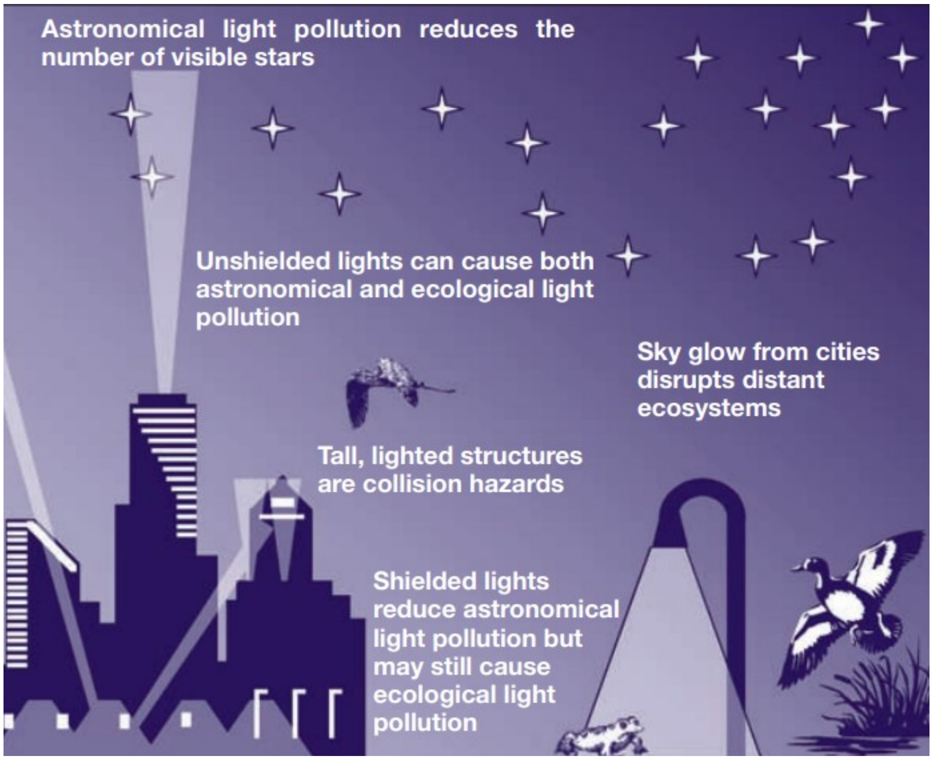

Figure 1.2: Diagram of astronomical and ecological light pollution from Longcore and Rich (2004).

The methods for reducing the two types of light pollution differ. Shielding lights downward and replacing bulb types can reduce the amount of astronomical light pollution (International Dark-Sky Association 2019), but these can sometimes increase the amount of ecological light pollution (Figure 1.2). Light intensity (lux), wavelength, and sudden changes can all negatively affect ecosystems. For example, high pressure sodium lights will attract moths while low pressure sodium lights of the same intensity will not, due to the differences in wavelengths they produce, which then impacts the behavior of bats that feed on moths (Rydell

1992). Large shifts in light can negatively impact the diel patterns of some organisms, such as nocturnal frogs that change their behavior when light patterns are changed (Buchanan 1993). All these aspects of light need to be accounted for when attempting to reduce ecological light pollution.

Mammals in Urban Areas

Like all wildlife groups, mammals have lower species diversity in urban settings (Mackin-Rogalska et al. 1988). This is especially true in the “urban core,” where there are few green spaces and impervious surfaces are expansive (Blair and Launer 1997). The lack of vegetation in urban settings is a strong predictor of species richness because mammal species richness is often correlated with vegetation cover (McKinney 2002). In a study on urban dwelling mammals in Oxford, Dickman (1987)found that including potential habitat patches that were highly disturbed by urbanization decoupled the relationship between vegetation and species richness. However, omitting highly disturbed patches and retaining urban patches with some green space showed that vegetation was impacting species richness of small mammals in urban settings (Dickman 1987). Remaining vegetation in urban landscapes is typically highly landscaped with reduced volume, meaning not all urban vegetation spaces can provide the resources that mammals require (Adams 1994).

Riparian corridors are an important green space for mammals in urban areas (Hilty and Merenlender 2004, Mahan and O’Connell 2005). In northern California, these riparian corridors allow a top predator like the cougar (*Felis concolor*) to persist within an urban center (Hilty and Merenlender 2004). Since riparian areas provide a forested area for mammals to shelter and find food resources (Mahan and O’Connell 2005), they act like forest edges, promoting greater species richness (Dickman 1987).

Not all mammals react to urbanization in the same way. While many large mammals [elk (*Cervus canadensis*), bison (*Bison bison*), moose (*Alces alces*), etc.], and especially large predators [brown bears (*Ursus arctos*), cougars (*Puma concolor*), gray wolves (*Canis lupus*), etc.], were displaced by urban environments as soon as European settlement began (Matthiae and Stearns 1981), others became urban adapters (McKinney 2002). Species such as raccoons, opossums, deer, coyotes, squirrels, and small mammals utilize forest edges and green spaces to persist in and around urban centers (Dickman 1987, Gehrt et al. 2013, Gallo et al. 2017).

Urbanization has disturbed communities in other ways, such as the introduction of alien species and increased invasion capacity (Schochat et al. 2010, Marques et al 2020). Non-native rodents such as the brown rat (*Rattus rattus*), the Norway rat (*Rattus norvegicus*), and the house mouse (*Mus musculus*) are invasive to the United States and they have been found in nearly every state across the country, residing almost exclusively within urbanized areas (King 1950). These invasive mammals can outcompete native mammals for food resources, disrupting urban mammal densities and community composition (Harper and Veitch 2006). As urbanization continues to increase, these disturbances will grow and continue to impact mammal communities.

ALAN and Mammals

Urbanization can impact mammals in multiple ways, including environmental pollution with ecotoxins (Shore and Douben 1994), noise (Slabbekoorn et al. 2018), and artificial light (Rich and Longcore 2013). Artificial light is less studied than other pollutants, but it can have multiple effects on mammals. One of the impacts of ALAN on mammals is altered movement patterns. Bliss-Ketchum et al. (2016) investigated the effects of ALAN on an Oregon wildlife passage and found that elevated artificial light reduced movement of Columbia black-tailed deer (*Odocoileus hemionus columbianus*), Virginia opossum (*Didelphis virginiana*), and deer mice (*Peromyscus maniculatus*). This also showed that a large-, medium-, and small-bodied species of mammal were impacted similarly by ALAN.

ALAN can also change predation in mammals. In a study on the vigilance in peahens, Yorzinski et al. (2015) observed that raccoons (*Procyon lotor*) and opossums (*Didelphis virginiana*) spent less time near a peahen enclosure when ALAN was present, while other potential prey animals such as mice (*Peromyscus spp.*), rabbits (*Sylvilagus floridanus*), and skunks (*Mephitis mephitis*) spent more time near the enclosure with ALAN present. This difference in prey and predatory behavior was thought to be due to increased prey vigilance in the presence of ALAN because the light allowed them to see predators earlier. This behavior is not consistent across all prey species. However, this behavior is not consistent across all species. De Molenaar et al. (2003) observed differences in movement patterns across earthen dams in the Netherlands when ALAN was present. Predators such as foxes (*Vulpes vulpes*), polecats (*Mustela putorius*), weasels (*Mustela nivalis*), and stoats (*Mustela erminea*) were more likely to cross dams with lighting while prey species like brown rats (*Rattus norvegicus*) avoided lighted dams.

Some mammals, especially small mammals and rodents can be impacted by ALAN by changing their foraging behavior. In a study on foraging of Stephen's kangaroo rats (*Dipodomys stephensi*), it was found that the rats, in this case the prey species, avoided patches with ALAN (Shier et al. 2020). This trend was also seen in the foraging behavior of the Santa Rosa beach mouse (*Peromyscus polionotus leucocephalus*; Bird et al. 2004). By creating multiple resource patches where light was present at some and absent at others, they saw significantly higher foraging behavior at unlit patches.

Some mammals, such as coyote (*Canis latrans*) and red foxes (*Vulpes vulpes*), are well adapted to urban environments, so much so that populations of coyotes and foxes have increased in density compared in urban settings compared to surrounding rural areas (Gehrt and Riley 2010, Bateman and Fleming 2012). Adaptation to urban environments can reduce the impact of artificial light on these carnivores. Bombieri et al. (2018) showed that wild carnivore attacks on humans occur in different locations based on how well adapted carnivores are to urban environments. Black bears (*Ursus americanus*), who are less adapted to urban environments, only had human-wildlife conflicts in areas with high vegetation density and low ALAN. Coyotes, who have higher population densities in urban centers, had human wildlife conflicts in areas with higher ALAN intensity, suggesting that their adaptation to urban environments allowed them to be bolder in the presence of ALAN.

ALAN can impact similar species of mammals differently. While some bat species such as the lesser horseshoe bat (*Rhinolophus hipposideros*) change their movement patterns to avoid artificial light across urban landscapes (Zeale et al. 2018), others do not change their flight patterns based on artificial light. The Daubenton's bat (*Myotis daubentonii*) was shown to maintain commuting corridors in the presence of multiple types of light, including white, red, and green (Spoelstra et al. 2018). When foraging, bat species that are fast moving with long-range echolocation systems will use ALAN to exploit insects that gather around light sources while slow flying species (e.g., *Myotis* spp.) avoid light sources (Rydell 1992, Zeale et al. 2018). Since ALAN affects are species-specific, more research needs to be done to understand how artificial light impacts mammal communities.

ALAN and Streams

Increasing urbanization impact streams in multiple ways, so much so that the term "urban stream syndrome" was coined to describe the effects of urbanization seen across many streams and rivers (Walsh et al. 2005). Some "symptoms" of urban stream syndrome include flashier flow in urban streams after rain events (Dunne and Leopold 1978), increases in chemical loads of pollutants (Hatt et al. 2004), increases in incision and channel erosion (Neller 1989), dominance of tolerant biota (Roth et al. 1996), and reduced nutrient uptake (Meyer et al. 2005). With so many stressors already impacting streams, the increase of urban lighting has also increased the likelihood that urban streams can also be impacted by ALAN. Streams and riparian zones are more likely to be impacted by ALAN due to increases in the development of waterways by cities (Kummu et al. 2011).

Ecological impacts of ALAN can affect all taxa in stream and river systems (Rich and Longcore 2013). Amphibians are one group that are susceptible to ALAN impacts. In a study done on a species of tailed frogs (*Ascaphus truei*), Hailman (1982) found that their emergence for foraging was impacted by the presence of artificial light. Tailed frogs typically forage during the darkest part of the night, so the presence of ALAN disrupted their emergence timing, which in turn impacted their foraging activity. Salamanders are also disrupted by ALAN, especially when it comes to predator avoidance. Some salamanders in the larval stages within streams will switch to more nocturnal activity to avoid predation (Sih et al. 1992). In the presence of ALAN, this switching of activity may not increase survival because predators will have greater visual acuity at night.

Fish activity can also be altered by ALAN. Juvenile rainbow trout (*Oncorhynchus mykiss*) were reduced foraging activity in the presence of artificial night lighting, with as little as a single light source along a stream being enough to disrupt their typical patterns (Contor and Griffith 1995). Migration patterns can be altered when ALAN is present. Sockeye salmon (*Oncorhynchus nerka*) fry delayed their downstream migration when artificial lighting intensity was low (~1 lux) and almost completely stopped at high levels (32 lux) with higher predation on migrating fry occurring with increased ALAN (Tabor et al. 2001). Prinslow et al. (1980) found a similar pattern in chum migrating through a canal, with increases in light levels delaying their migration.

The major prey items of both fishes and amphibians within streams, invertebrates, are also impacted by ALAN. Aquatic invertebrates that emerge from an aquatic larval stage to an aerial adult stage (henceforth referred to as emergent invertebrates) can be attracted to artificial light sources. A study in Germany found that emergent invertebrate density within dark zones compared to lighted zones was much higher, indicating richer insect fauna where artificial light was not present (Scheibe 1999). This could be due to a "vacuum cleaner" effect of streetlamps, an ecological trap when ALAN is present that attracts invertebrates to light sources where bat predation and mortality are likely to occur. Tobias (1996) observed this effect with mayflies, referring to the phenomenon as "summer snow" due to the amount of mayflies covering bridges when light is present. Invertebrates can also be impacted within streams, with artificial light changing or removing visual cues to initiate drift (Rich and Longcore 2013).

ALAN impacts communities within streams, as well as linkages between streams and riparian areas. Aquatic energy sources can be important contributors to terrestrial food webs in the form of emergent invertebrates that are consumed by terrestrial predators (Kautza and Sullivan 2016). Since emergent invertebrate densities are impacted by ALAN, one could infer that those aquatic-riparian linkages could be altered. In a study done by Meyer and Sullivan (2013) on aquatic-riparian linkages in Columbus, OH, they found a decrease in tetragnathid spider density. These spiders get a large proportion of their diet from emergent invertebrates. In a similar study, Sullivan et al. (2019) found changes in food chain length and the reliance of aquatically derived energy to terrestrial consumers. With so many taxa within streams being impacted by ALAN, more research needs to be done to understand how these individual or population impacts change communities and ecosystems.

Objectives

Numerous studies have been conducted on the ecological impacts of ALAN, but few have examined how ALAN impacts mammals in urban riparian zones. The goal of my project was to study how ALAN impacts urban mammal communities' diet and space use in small-order streams. This work expands on ALAN research within the same system. Specifically, my research objectives were to:

1. Investigate the influences of ALAN on riparian mammal community composition and space use.

2. Investigate the diets of riparian small mammals and the relative reliance on terrestrial versus aquatic nutritional subsidies in lit and unlit reaches.

While the study was conducted within the Columbus Metropolitan Area, I anticipate the results will be applicable to similar cities within the Midwestern United States, helping to inform management guidelines for roadway lighting and city-based light ordinances.

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Chapter 2: Mammal Communities Show Muted Habitat-use Response to Artificial Lighting at Night

Abstract

Artificial light at night (ALAN) is a growing environmental stressor driven by both expanding urbanization and the increasing global electric footprint. ALAN has been shown to impact mammal movement and habitat-use preference at the individual and population levels of biological organization. However, there is limited evidence relative to the potential impacts of ALAN at the community level. I investigated the impacts of ALAN (0.1-2.5 lux) on riparian mammal community space use along 12 urban headwater streams in Columbus, Ohio, USA. No species-specific small mammal captures or species/guild-specific camera-trap encounters were associated with ALAN presence. Seasonality and sediment size, but not ALAN, were associated with total mammal encounters and species richness. Site, as a random effect in linear-mixed models, explained more than half of the variation in both encounters and species richness, implicating other local characteristics such as proximity to additional green spaces, continuity of green space through the urban center, and overall urbanization of the area as drivers of mammal communities. Sediment size was likely a proxy for either stream size or urbanization but also a potentially important structural factor related to small-mammal movement across streams. Seasonality and time of day were the strongest drivers of mammal community composition along streams, despite the presence of ALAN. Overall, I found no evidence that ALAN was associated with mammal space use or community composition in these riparian areas. These results suggest that, at the lighting levels of this study, the importance of riparian areas and tolerance of urban mammals overrides any ALAN impacts at current light levels, which can be used to help develop roadway lighting thresholds.

Introduction

Artificial light at night (ALAN) is an environmental stressor generated by a single artificial lighting source, multiple artificial light sources shining directly on an area, or the reflectance of many artificial light sources in the form of sky glow (Longcore and Rich 2004). With the worldwide increase in urbanization, the percentage of the Earth’s surface exposed to ALAN has also expanded (Utzinger and Keiser 2006). It is estimated that 23% of land surface between 60°S and 75°N is exposed to skyglow (Falchi et al. 2016) and 22% of all coastal regions are experiencing increases in artificial illumination (Davies et al. 2014). Most studies on the ecological impacts of ALAN, also known as ecological light pollution (Longcore and Rich 2004), have focused on the individual or population level and on behavioral responses to organisms to ALAN. For example, ALAN can alter foraging behavior in herpetofauna (Hailman 1982), migration timing in fish (Prinslow et al. 1980, Tabor et al. 2001), and movement patterns of mammals (de Molenaar et al. 2003, Rotics et al. 2011, Bliss-Ketchum et al. 2016). Fewer studies have focused on community or ecosystem-level processes (Sanders and Gaston 2018, Zapata et al. 2019). For instance, Sullivan et al. (2019) observed moderate-to-high levels (0.6-4.0 lux) of ALAN altered invertebrate community composition by favoring predators and detritivores.

Mammals are an important component of urban ecological communities. Mammals such as coyotes (*Canis latrans*) are often the top predators in urban settings where larger or less adapted predators struggle to persist (Gehrt and Riley 2010). Some mammals can exhibit higher population abundances within cities than outside of them due to their ability to adapt and use resources within urban centers (Dickman 1987, Gehrt et al. 2013, Gallo et al. 2017). Urban mammals commonly utilize green spaces such as golf courses and city parks to persist within a city (Gallo et al. 2017). Stream riparian areas serve as important green spaces for mammals that provide cover and food resources (Mahan and O’Connell 2005). Riparian forests within cities foster faunal diversity by acting like forest edges, creating a type of ecotone (Dickman 1987). Hilty and Merenlender (2004) observed that riparian forests were used by mountain lions (*Puma concolor*) to traverse urban areas along with other mammal species that would have otherwise been stopped by buildings and impervious surfaces, showing that riparian areas can be used as movement corridors within cities. Riparian areas are also more vulnerable to the impacts of ALAN. Many cities were built around and have developed along waterways, leading to riparian zones being highly exposed to ALAN (Kummu et al. 2011).

Different species of mammals respond differently to environmental perturbations. Some mammals, often rodents and other small mammals, can be indicators of disturbance within an ecosystem (Pearce and Venier 2005). For example, Romañach et al. (2020) found increased abundance of cotton mouse (*Peromyscus gossypinus*) populations and higher presence of marsh rice rats (*Oryzomys palustris*) in restored wetlands compared to disturbed wetlands. Pearce and Venier (2005)found that red-backed voles (*Clethrionomys gapperi*) abundance had a negative relationship with clear cutting while deer mice (*Peromyscus maniculatus*) were strongly associated with recently clear-cut areas on small mammals in boreal forests in Canada, illustrating divergent responses to the same perturbation. Other mammals within a community, such as whitetail deer (*Odocoileus virginianus*) and raccoons (*Procyon lotor*) are resistant to many anthropogenic disturbances and are not good indicators of urban environmental pressures (Gallo et al. 2017).

Similarly, mammals exhibit different responses to ALAN. Shier et al. (2020) found that kangaroo rat (*Dipodomys stephensi*) would change their foraging behavior to avoid both high- and low-quality foraging patches under ALAN produced by 756 lumen LED light. The researchers suspected that the rats were avoiding the ALAN patches to avoid predation. De Molenaar et al. (2003) observed that some mammalian predators were more likely to use dams where lighting was present at ~27 lux while other species were not similarly affected. Bliss-Ketchum et al. (2016) found artificial light in under-road passage structures in Oregon acted as a barrier to movement and reduced habitat connectivity for some mammals at ~150 lux yet did not impact others.

Responses to ALAN can also be mediated by light intensity and spectral composition. In a study of peahens' nocturnal vigilance and avoidance of mammalian predators, Yorzinski et al. (2015) found that high levels of artificial lighting (~3.0 kLux) elicited a greater roosting response, while low levels of light (0.75 lux) showed no change. Ohlberger et al. (2008) found that two different fishes in Germany had higher feeding rates and greater foraging activity at higher lux levels (~5 lux). Differences in the wavelength and light spectrum that the lights emit can also change how species react to ALAN (reviewed in Gaston and Bennie 2014, Stone et al. 2015b, Desouhant et al. 2019). For instance, Stone et al. (2015a) found greater bat activity by multiple species at newly installed metal halide lights than at low-pressure sodium (LPS) lights, implicating the broader wavelength spectrum emittance of metal halide lighting as a potential mechanism.

We compared terrestrial small mammal, total mammal, and mammal feeding-guild diversity and community composition between riparian zones of small streams with and without ALAN in the Columbus Metropolitan Area (Columbus, Ohio, USA). We hypothesized that ALAN would lead to a decrease in perceived small mammal abundance, estimated by mark-recapture methods or total captures, due to predator avoidance behavior and changes in foraging behavior. Owing to the expectation that tolerant mammal species would disproportionately utilize lit reaches, we also predicted that total mammal community diversity would decrease in reaches with ALAN (as measured by Relative Abundance Indices (RAI's) and species richness from camera-trap encounters). We also predicted that small and large predator guilds would have a greater encounter rate at lit reaches compared to unlit reaches while small prey guilds would have fewer encounters at lit reaches, as measured by camera trap encounters, due to predators using increased lighting to assist with hunting success while small prey would exhibit predator avoidance in those areas. In addition to ALAN presence, we hypothesized that our relationships based on our predictions would be stronger under (1) higher ALAN intensity and (2) at sites with light emitting diode (LED) lights compared to high pressure sodium (HPS) lights due to LED's emitting a wider spectrum of light with a greater chance of emitting a wavelength that would negatively impact mammals. We explored the influences of stream geomorphology (sediment size), riparian vegetation characteristics (canopy cover), and relative urbanization of the riparian areas as potential mechanisms linked to changes in mammal communities.

Methods

Study Sites

The Columbus Metropolitan Area (hereafter CMA) spans 8,208 km^2 in central Ohio with a population of 2.4 million people. The CMA is in the Scioto River Watershed and is characterized by the Scioto River flowing through it. The Scioto River is a 6th-order tributary of the Ohio River that drains a 16,882-km^2 basin throughout Ohio (Reick and Sullivan 2020). The upper section of the basin where the Scioto River flows through Columbus, is mostly row-crop agriculture north of the city and suburban/urban land use moving towards the city (Nelson 2014). Ten paired lit-unlit 1st-3rd order stream-riparian sites were selected for our study, based on previous knowledge of the system (Sullivan et al. 2016, Sullivan et al. 2019, Rieck and Sullivan 2020) and synoptic surveys of ALAN intrusion into riparian zones (Figure 2.1). The following criteria were used in site selection: light source (streetlights, house lights, yard lights, etc.) was present over a 30 m stretch of a stream (i.e., lit reach), light intensity at night over the lit reach averaged between 0.28 and 3.5 lux (typical light intensity values for canopied streams in the CMA were 0.01-4.0 lux, Sullivan et al. 2019); upstream from the lit reach was an unlit 30-m reach of the same stream with similar geomorphic, terrestrial vegetation, and flow features

(Figure 2.2); upstream reach was not impacted by ALAN; there were no barriers (e.g., artificial flow obstructions, bridges) or additional water inputs (e.g., drainage pipes, tributaries) between the two paired study reaches. Two additional sites (i.e., two paired unlit-unlit) - one within the CMA and one was in a rural area 70 km northwest of Columbus to avoid urban impacts – served as reference sites. Unlit reaches were always located upstream from lit reaches to prevent downstream flow impacts from lit reaches being recorded at unlit reaches.

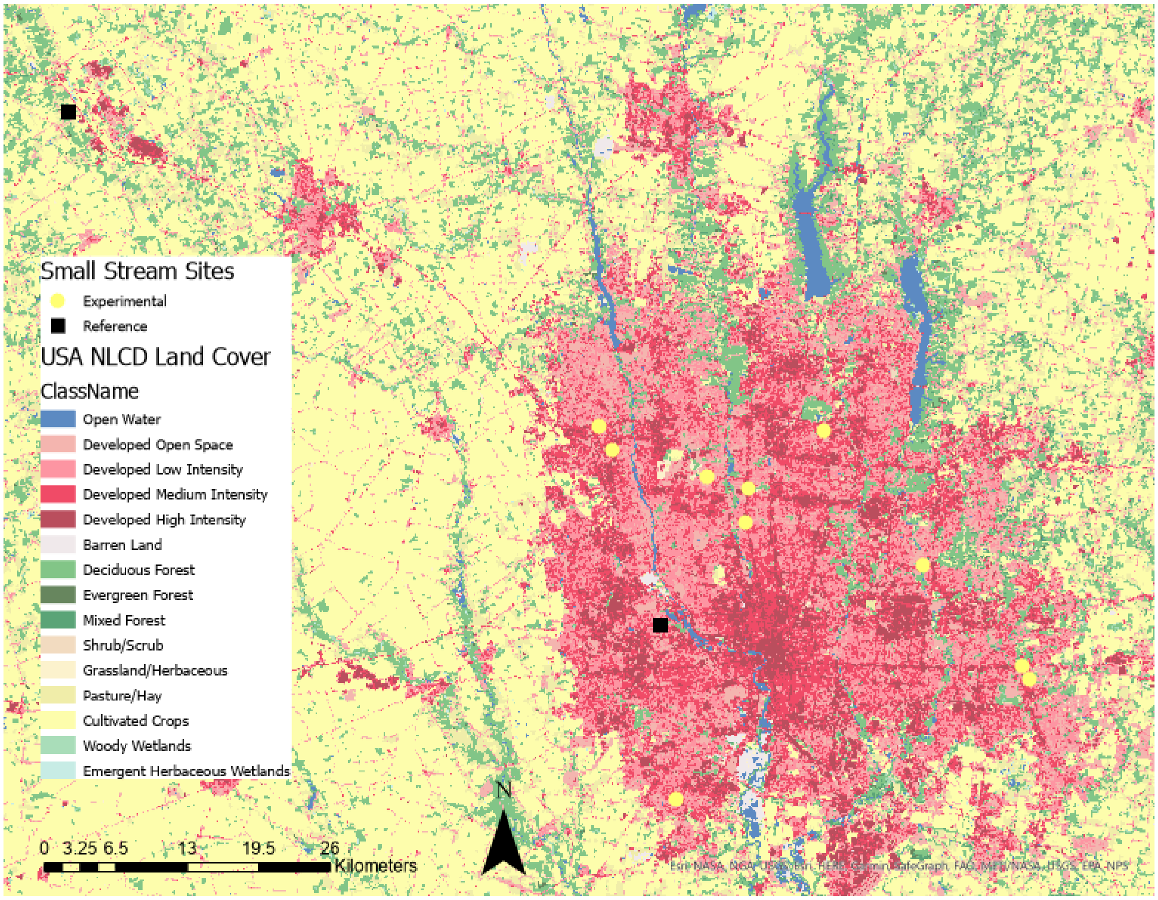


Figure 2.1: Map of experimental sites with paired lit-unlit reaches (yellow dots) and reference sites with paired unlit-unlit reaches (black squares) over 2021 NLCD Land Cover data.

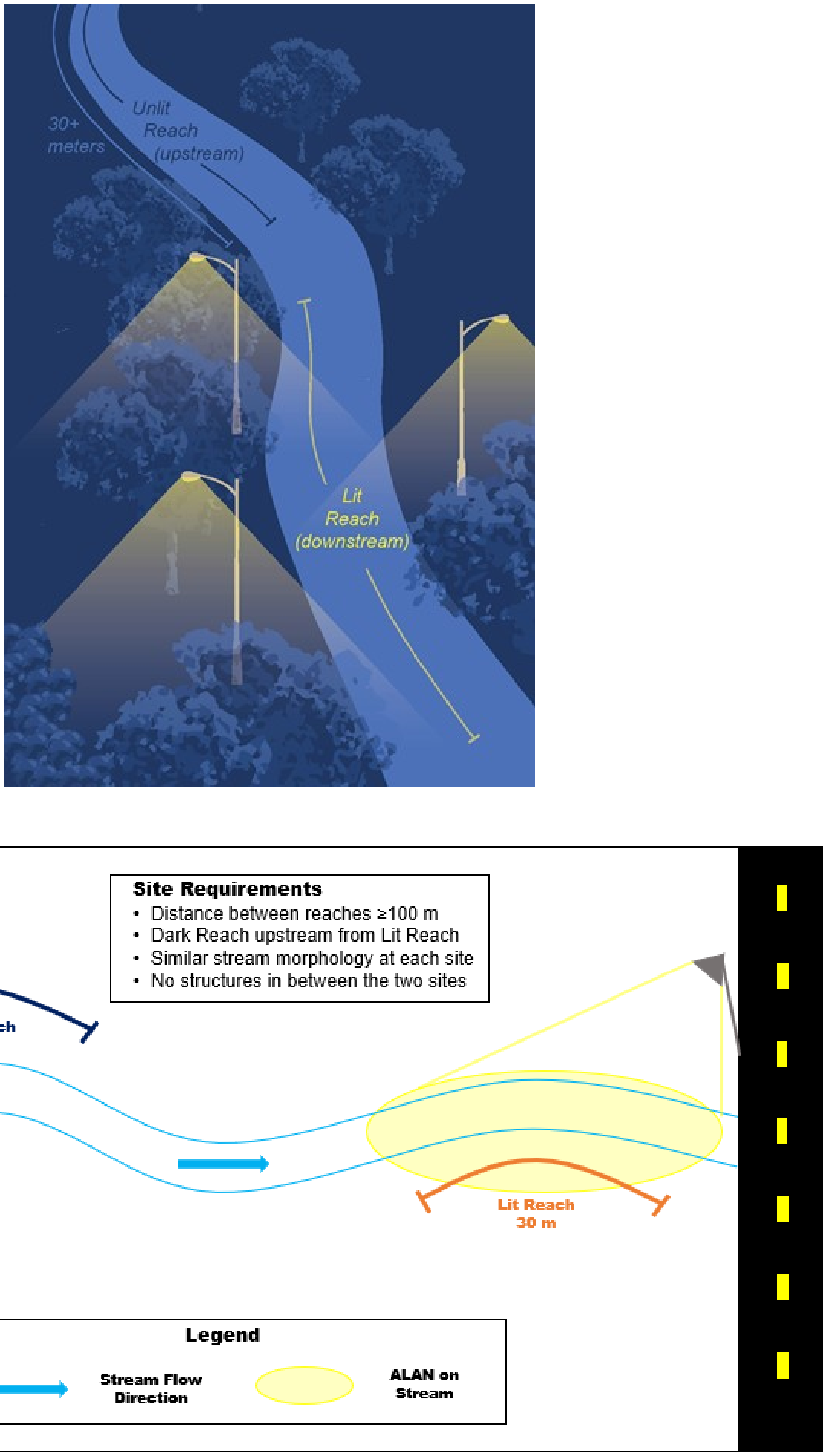


Figure 2.2: Experimental design: (a) at each lit-unlit pair of stream reaches (i.e., site) and (b) at each site with a nearby road and site requirements. The lit reach was downstream from the dark/unlit reach to prevent the unlit reach from having downstream impacts from ALAN.

Small Mammal Trapping

Small mammals were trapped using Sherman live traps (7.62 x 8.89 x 22.86 cm, galvanized steel doors and treadle; H.B. Sherman Traps, Tallahassee, Florida, USA) in a paired transect design (Pearson and Ruggiero 2003). Each transect contained seven pairs of traps (14 total) to accommodate multiple captures at the same location, with each pair of traps spaced 5 m from other pairs. Transects ran parallel to the stream, 5 m from the stream bank. Trapping transects were opened for three consecutive nights at each reach, with the lit and unlit reach of each paired study site being trapped concurrently. Traps were baited with a mixture of oats and peanut butter with cotton ball bedding included. Trapping occurred from August 2020 to November 2021, with each site being sampled three times, once in the late summer/early autumn of 2020, once in the summer of 2021, and once in the autumn of 2021. All trapping was carried out in accordance with the standards set by the OSU Institutional Animal Care and Use Committee (IACUC, Protocol 2010A0003-R3).

All captured small mammals were placed in handling bags to reduce stress (Sikes et al. 2011). Standard measurements were taken on all captures as well as recording age class, sex, and species identification. Identifications were based on guidelines from Gottschang (1981). Ear tags (1005-1 Ear Tags, National Tag and Band Company International Identification Inc., Newport, KY, USA) were attached to a single ear all captured individuals to record mark-recapture data. For shrews that cannot have ear tags, we used permanent marker color patterns on their ventral side to create individualized marks. All captured small mammals were released at the same place they were captured.

Camera Trapping

Presence of larger mammals was assessed with RECONYX Hyperfire 2 High-Output Trail Cameras (RECONYX, Holmen, Wisconsin, USA) that were deployed at paired reaches simultaneously with live-trapping periods. Two cameras were deployed at each reach , one each at lit/unlit reaches in four separate sampling events: May - June 2021, July 2021, October – November 2021, and January – February 2022. Cameras were set for 10 consecutive days during each sampling period and all pictures were digitally stamped with the date and time.

All cameras were attached to trees ~1 m above the ground with a field of view that encompassed the entire 30 m reach. Cameras were set facing away from trails, roads, or any high human usage area and followed the recommendations of Herrera et al. (2021). Cameras were set to a three-shot trigger, a 5 second delay between triggers, and activated IR flash for nighttime photographs. Due to difficulty in identifying different individuals, mammals of the same species observed by the camera within 20 minutes of the most recent sighting were considered a single independent encounter, unless multiple individuals were observed at a single time. Observations of the same species outside of 20 minutes of the most recent encounter, even if they are potentially the same individual, were considered separate independent encounters. Sites that were compromised by damaged or destroyed camera traps were resampled during the following 10 days. Encounters during both daytime and nighttime were included in analysis due to ALAN potentially impacting the timing of activity of nocturnal animals, creating changes to daytime encounters.

Environmental Variables

Light illuminance (lux) was measured on three transects (0m, 15m, 30m), two positions (left-middle, right-middle), and three heights (1cm below water surface, 1cm above surface, 1m above surface) using an ILR 1700 Radiometer with a waterproof illuminance (lx) sensor (SUD033/Y/W; International Light Technologies, Peabody, Massachusetts). Spectral composition of primary light sources was recorded using an Ocean Optics® Flame UV-VIS Spectrometer (Ocean Insight, Orlando, Florida). Light sources at each site were categorized as either high-pressure sodium (HPS) or light-emitting diode (LED) based on spectral distribution. Illumination and spectra were measured at each reach during Summer 2019, Autumn 2019, Winter 2020, Summer 2020, Autumn 2020, and Winter 2021 at least two hours after sunset on nights without cloud cover.

Canopy cover was measured from canopy photographs photographed with a fish-eye lens camera during sampling periods in 2019, 2020, and 2021. Impervious surface distance (the shortest distance from the stream to an impervious surface) was measured four times at 10-meter increments along each reach using the “Measure” function in ArcGIS Pro (ESRI 2019) to quantify urbanization of each reach. Following Wolman (1954), sediment size was measured using a gravelometer at the top, middle, and bottom of each reach by completing pebble counts with a minimum of 75 pebbles to estimate the median sediment size (D_{50}) during Spring 2021.

Statistical Analysis

Linear mixed-effect models (LMMs) were used to assess differences in total mammals encountered and species richness (*S*) between reaches. Season, time of day, light intensity (lux), light technology, impervious surface, sediment size (D_{50}), and reach were included as fixed effects in the models. Site was included as the random effect.

The amount of variation explained by site (the random effect) in the LMMs is the difference between the total variation of the model (Conditional R^2) and the variation of the model explained by fixed effects (Marginal R^2).

Analysis of mammal community composition was conducted in three ways: small mammal captures, camera-trap species encounters, and camera-trap guild encounters. For small mammal captures, abundance was estimated at each reach using two capture-recapture models: the Cormack-Jolly-Seber Model (CJS model) and Pollock's Robust Design. The CJS model used capture-recapture data with survival intervals between sampling events, meaning estimates of abundance and survival/emigration can be estimated from at least three sampling events (Cormack 1964, Jolly 1965, Seber 1965). Pollock's Robust Design integrates the CJS model with multiple sampling events, known as "trapping intervals," occurring between survival intervals. This allows for estimation of abundance, survival/emigration, and birth/immigration (Pollock 1982). While attempting to use the white-footed mouse data, the small sample sizes resulted in the Cormack-Jolly-Seber and Pollock's Robust Design mark-recapture models not providing reliable estimates of population parameters (Appendix B). All further analysis was done on raw capture data rather than abundance estimates, with the number of captures summarized by site, reach, and season available (Appendix C). At each level (small mammal captures, camera-trap species encounters, camera-trap guild encounters), the most encountered species/groups were compared at lit versus unlit reaches using paired *t*-tests.

To measure the difference between reaches based on their species/guild compositions, Bray – Curtis dissimilarity was calculated for all reaches. Bray – Curtis dissimilarity is calculated using a matrix where each row is a different reach and each column is a different species/guild, with the values of the matrix being the number captured/encountered at that reach.

The Bray – Curtis dissimilarity value is a non-Euclidian distance measure that quantifies the differences between samples of ecological abundance data at different locations (Bray and Curtis 1957). Bray – Curtis dissimilarity dendrograms for each level graphically displaying the differences are available in Appendix D.

Species and guild compositions were also qualitatively assessed using non-metric multidimensional scaling (NMDS) plots with convex hulls representing fixed effects. NMDS plots allow for the projection of reaches into a 2-dimensional plot based on multi-dimensional factors (in this case, species/guilds). Following Anderson (2001), Permutational Multivariate Analysis of Variance (PERMANOVA) was used to analyze the effects of year, sediment size, impervious surface, and season on small mammal capture community, the effects of time of day, reach, sediment size, impervious surface, and season on total mammal camera-trap capture community, and the effects of time of day, reach, sediment size, impervious surface, and season on mammal guild camera-trap encounter community. PERMANOVAs were performed using the Bray-Curtis distance matrix with blocking by site ($n_{perms} = 9999$). Additional ALAN variables (light intensity, spectral composition) were removed from the analysis due to violations of dispersion.

All data analysis was completed in R (R Core Team 2018) using base packages and the **vegan** package (Dixon and Palmer 2003). In all statistical tests, an $\alpha = 0.05$ ($p < 0.05$) was used to indicate statistical significance; an $\alpha = 0.10$ ($p < 0.10$) was used to indicate a trend of possible differences under a greater sample size or different lighting regime.

Results

Lighting Sources

The two types of lighting found at the different sites were mixtures of high-pressure sodium (HPS) and light emitting diode (LED) lights that emitted different wavelengths (*Figure 2.3*). LED lights emitted a wider range of wavelengths than HPS wavelengths. There were significant differences in average lux values at night between lit and unlit reaches at the same sites (*Figure 2.4*). Mean lux values at lit reaches ranged from less than 0.5 lux at the Palmer site to almost 3 lux at the Sycamore site. Most lit sites had average nighttime lux values between 0.6-2 lux.

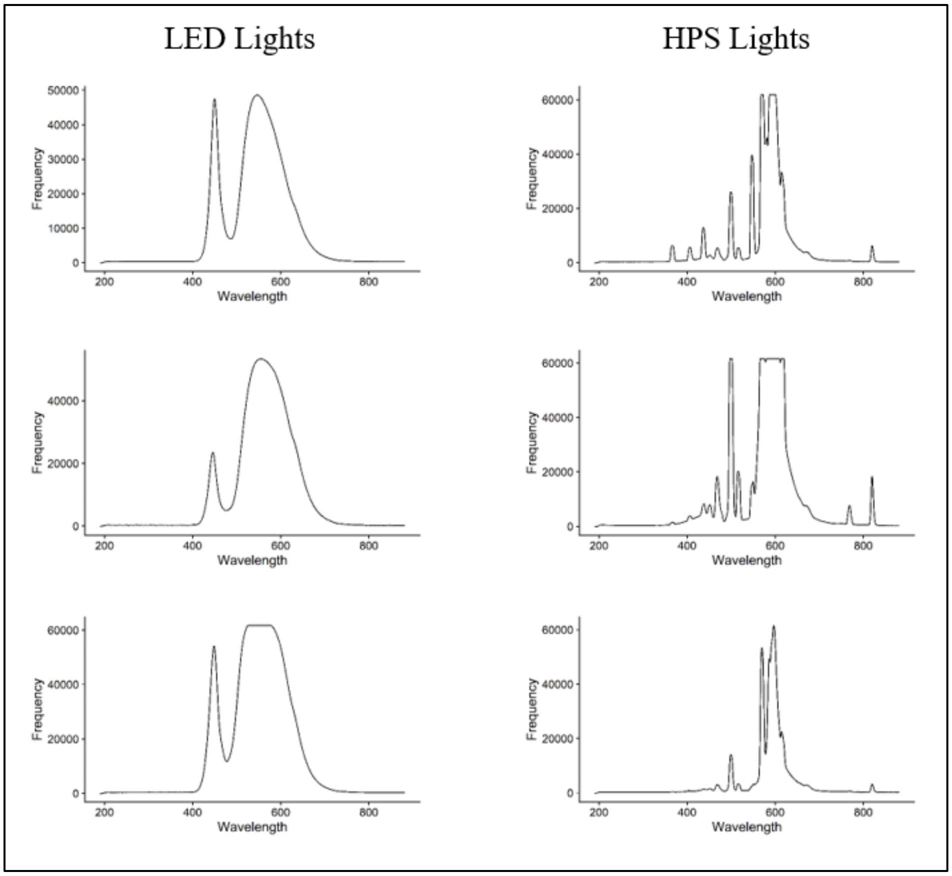


Figure 2.3: Spectral graphs of wavelength and frequency for LED and HPS lights at experimental sites. There was variation between lights at different sites [LED: Noble (top), Dublin Rec (middle), Rita's (bottom); HPS: Cosgray (top), VFW (middle), Sycamore (bottom)] but a visible difference between LED and HPS spectral graphs.

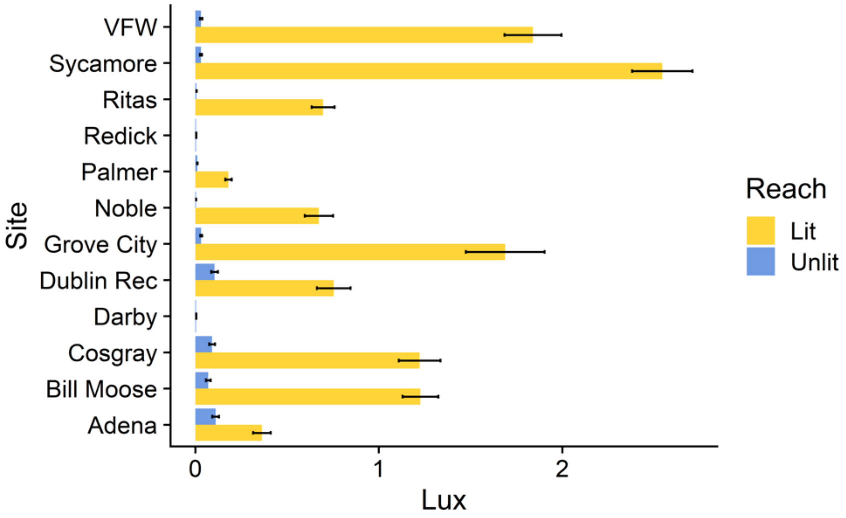


Figure 2.4: Mean lux values at night comparing lit and unlit reaches. Error bars= +/- 1 SE. None of the reaches at reference sites (Darby, Redick) exhibited any lux values high enough to register on the ILT1700.

Mammal Captures/Encounters

A total of 257 captures of 6 small mammal species (Table 2.1) was recorded over 3,024 trap nights, with 210 of those captures occurring at the experimental sites. There were 58 recaptures at all sites and 49 recaptures at experimental sites. The species with the most captures was the white-footed mouse (*Peromyscus leucopus*).

There were no significant differences in captures of any species between lit and unlit reaches (paired t-test: p = 0.184-0.343; *Table 2.1*). Individuals from the genus *Peromyscus* that could not be identified to species were listed as *Peromyscus spp*. Both encounters of Virginia opossum (*Didelphis virginiana*) were juvenile individuals that were captured on the same day at the same reach.

Table 2.1: Total captures for small mammal species within riparian stream reaches of the Columbus Metropolitan Area for lit and unlit reaches at paired study sites, the number of reaches at which each species was captured (# of reaches), and the number of captures at lit and unlit reaches. Species with >5 captures have results of paired *t*-test comparing the number of captures of that species at lit vs unlit reaches. Paired *t*-tests were not run for the unidentified deer mouse species since those individuals could have been two different species.

Common Name	**Species Name**	**Captures**	**# of Reaches**	**Captures - Lit Reaches**	**Captures - Unlit Reaches**	***t***	***df***	***p***
White-footed Mouse	*Peromyscus leucopus*	168	18	72	96	-1.439	9	0.184
Eastern Chipmunk	*Tamias striatus*	13	10	9	4	1.342	9	0.213
Deer Mouse Species	*Peromyscus spp.*	9	5	4	5	-	-	-
Short-tailed Shrew	*Blarina brevicauda*	9	6	6	3	1.152	9	0.279
Deer Mouse	*Peromyscus maniculatus*	8	5	3	5	-1.000	9	0.343
Virginia Opossum	*Didelphis virginiana*	2	1	2	0	-	-	-
Meadow Vole	*Microtus pennsylvanicus*	1	1	0	1	-	-	-

A total of 2083 independent encounters of 18 mammal species (Table 2.2) was recorded over 960 camera trap nights, with 1767 encounters of 17 mammal species occurring at the experimental sites. The most encountered mammals were white-tailed deer (*Odocoileus virginianus*), eastern gray squirrels (*Sciurus carolinensis*), and raccoons (*Procyon lotor*) (*Table 2.3*). Red squirrels (*Tamiasciurus hudsonicus*), fox squirrels (*Sciurus niger*), and white-footed mice (*Peromyscus leucopus*) were only encountered at two separate reaches each, while minks (*Neogale vison*) and domestic dogs (*Canis lupus familiaris*) were only observed at a single reach each. Domestic dogs were only counted when they were not on a walk with a human and the single domestic dog encounter occurred simultaneously with a domestic cat (*Felis catus*) encounter.

As with small mammals, we observed no differences between lit and unlit reaches for any of the encountered species (paired t-test: $p > 0.05$) (*Table 2.2*). Eastern chipmunks, Virginia opossums, and white-footed mice were the only species that were both captured by small mammal traps and recorded through camera-trap encounters.

Table 2.2: Relative Abundance Index (RAI – independent encounters/100 trap nights) for mammal species within riparian stream reaches of the Columbus Metropolitan Area for lit and unlit reaches, the total number of encounters for each species, and the number of reaches each species was observed at (# of reaches). Species with >20 encounters have results of paired t-test comparing the number of encounters of that species at lit vs unlit reaches.

Common Name	**Species Name**	**Encounters**	**# of Reaches**	**RAI - Lit Reaches**	**RAI - Unlit Reaches**	***t***	***df***	***p***
Whitetail Deer	*Odocoileus virginianus*	613	20	88.5	64.75	1.0262	9	0.3316
Eastern Gray Squirrel	*Sciurus carolinensis*	503	20	69.5	56.25	0.35835	9	0.7283
Raccoon	*Procyon lotor*	424	16	60.25	45.75	0.58388	9	0.5736
Red Fox	*Vulpes vulpes*	72	6	8.5	9.5	-0.1745	9	0.8653
Eastern Chipmunk	*Tamias striatus*	50	5	3	9.5	-1.0419	9	0.3246
House Cat	*Felis catus*	47	10	3.25	8.25	-0.9632	9	0.3606
Eastern Cottontail	*Sylvilagus floridanus*	32	6	3	5	-0.8300	9	0.4280
Virginia Opossum	*Didelphis virginiana*	25	5	2.75	3.5	-0.3448	9	0.7381

Continued

Table 2.2 Continued

Groundhog	*Marmota monax*	18	7	0.25	4.25	-	-	-
Coyote	*Canis latrans*	13	6	2	1.25	-	-	-
Long-tailed Weasel	*Mustela frenata*	12	4	0.5	2.5	-	-	-
Red Squirrel	*Tamiasciurus hudsonicus*	10	2	2.25	0.25	-	-	-
Striped Skunk	*Mephitis mephitis*	6	3	0.75	0.75	-	-	-
Fox Squirrel	*Sciurus niger*	5	2	0.5	0.75	-	-	-
Mink	*Neogale vison*	3	1	0.75	0	-	-	-
White-footed Mouse	*Peromyscus leucopus*	2	2	0.25	0.25	-	-	-
Domestic Dog	*Canis lupus familiaris*	1	1	0	0.25	-	-	-

Mammal species encountered using camera traps were broken down into four separate guilds based on feeding behavior and body size: large predators, small predators, large prey, and small prey. Red foxes, domestic dogs, and coyotes (*Canis latrans*) were assigned the large predator guild. Groundhogs (*Marmota monax*) and white-tailed deer were assigned the large prey guild. Virginia opossums, house cats, striped skunks (*Mephitis mephitis*), long-tailed weasels (*Mustela frenata*), minks, and raccoons were assigned the small predator guild. White-footed mice, eastern gray squirrels, fox squirrels, eastern cottontails, eastern chipmunks, and red squirrels were assigned the small prey guild.

The most encountered guild was large prey, followed by small prey, small predators, and large predators. Like previous results, there were no differences in encountered guilds between lit and unlit reaches (paired *t*-test: $p > 0.05$) (*Table 2.3*). Both prey guilds had a higher diurnal encounter rate while both predator guilds had a higher nocturnal encounter rate.

Table 2.3: Camera trap encounters for mammal guilds within riparian stream reaches of the Columbus Metropolitan Area for lit and unlit reaches, the total number of encounters for each guild, the number of reaches each species was observed at (# of reaches), and the percent of nocturnal encounters (>1 hour after sunset and >1 hour before sunrise. Paired *t*-test results comparing each guild encounters at lit vs unlit reaches are included.

Guild	Total Encounters	# of Reaches	Encounters - Lit Reaches	Encounters - Unlit Reaches	*t*	*df*	*p*	Percent Nocturnal

Continued

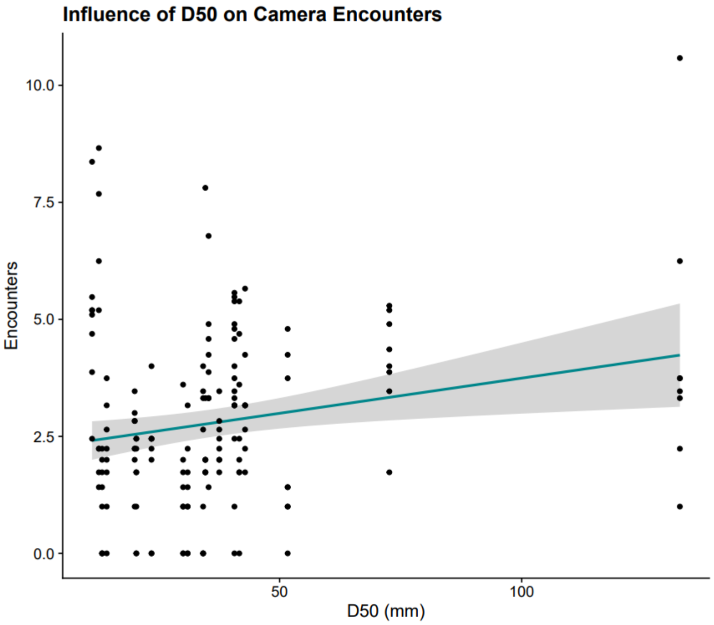
Table 2.3 Continued

Large Prey	631	20	355	276	0.846	9	0.419	40%
Small Prey	602	20	314	288	0.177	9	0.864	4%
Small Predator	516	16	273	243	0.121	9	0.906	92%
Large Predator	86	9	42	44	-0.081	9	0.937	92%

Linear Mixed-Effect Models

The number of camera-trap encounters ($R^2 = 0.043$, $F = 7.123$, $p = 0.008$) was positively associated with sediment size (*Figure 2.5*).Camera trap encounters were not associated with reach, light intensity, or light technology (i.e., the three ALAN variables we measured). However, camera-trap encounters ($R^2 = 0.064$, $F = 3.567$, $p = 0.016$) were associated with season as well.

(a)



Continued

Figure 2.5 Continued

(b)

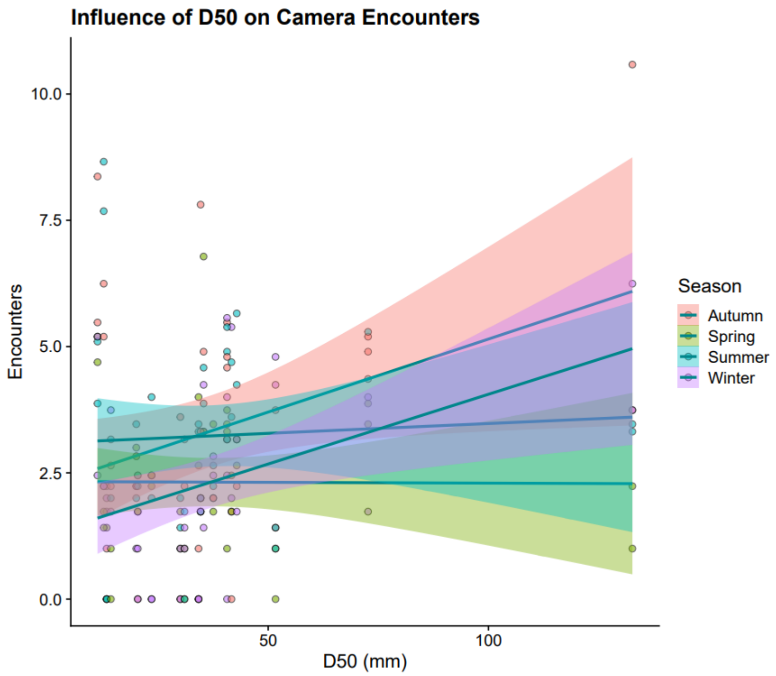


Figure 2.5: Linear relationship between: (a) sediment size (D_{50}) and total mammal encounters ($R^2 = 0.043$, $F = 7.123$, $p = 0.008$) and (b) sediment size (D_{50}) and season with total mammal encounters. Confidence curves represent 95% C.I.

Species richness (S) from camera trap encounters ($R^2 = 0.058$, $F = 9.774$, $p = 0.002$) was also positively associated with sediment size (*Figure 2.6*). As with encounters, species richness was not associated with any of the ALAN variables but there was a trend associated with season ($R^2 = 0.045$, $F = 2.429$, $p = 0.067$).

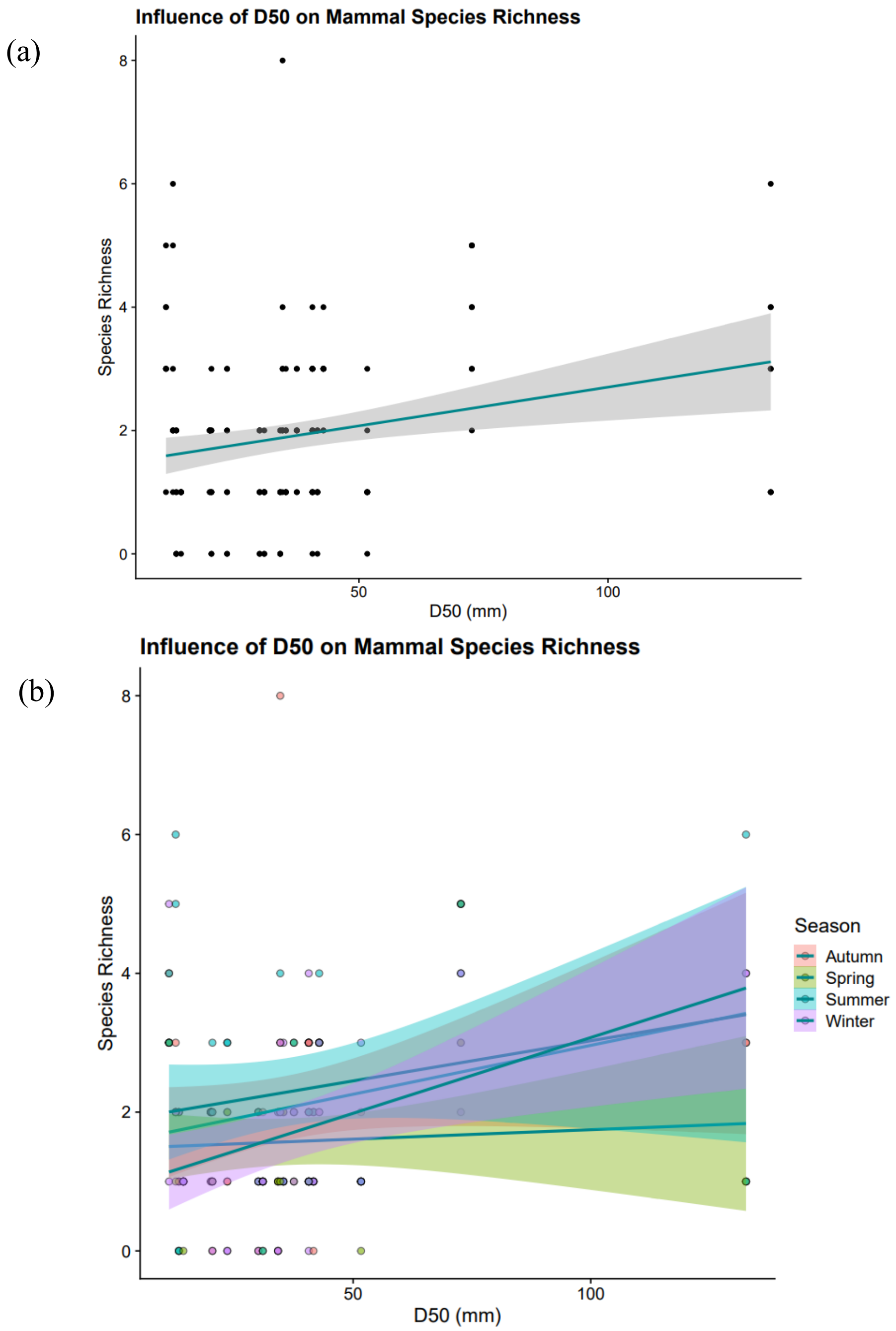


Figure 2.6: Linear relationship between: (a) sediment size (D50) and mammal species richness (R^2 = 0.058, F = 9.774, p = 0.002) and (b) sediment size (D_{50}) and season with total mammal encounters. Confidence curves represent 95% C.I.

Community Analysis

Results from the NMDS comparing the influence of season and year on small mammal species capture compositions (*Figure 2.7*) suggest potential seasonal and annual differences in small mammal species capture composition, but no difference by ALAN.

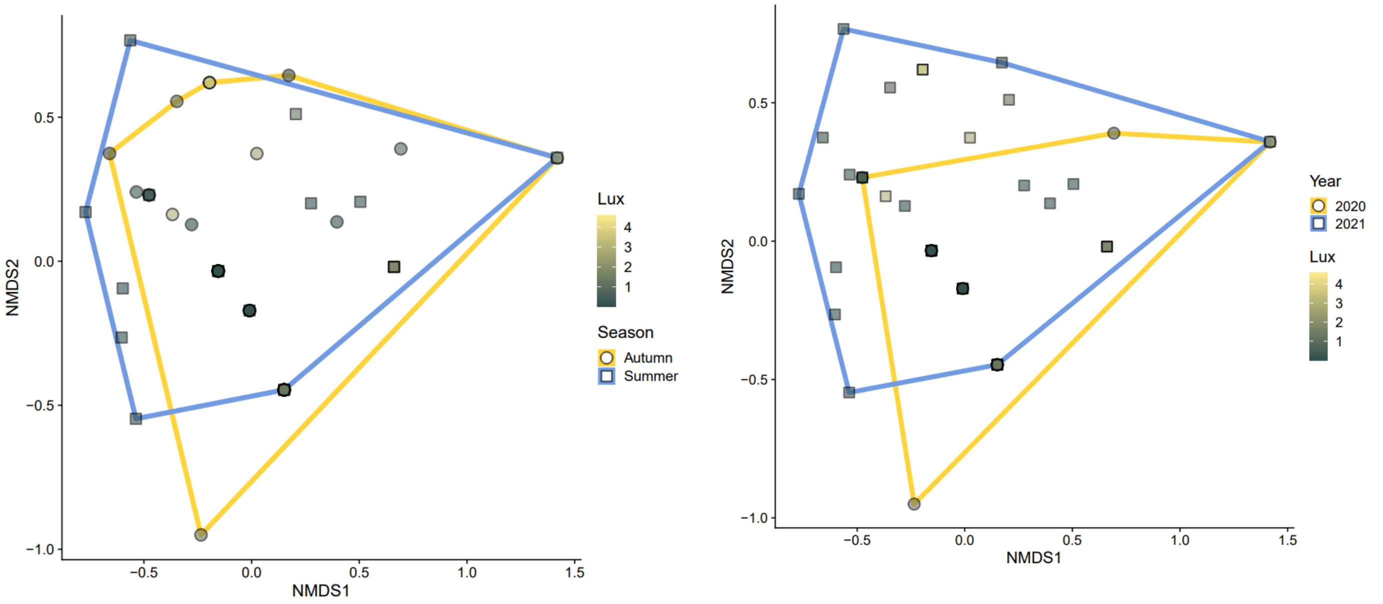


Figure 2.7: 2-D nonmetric multidimensional scaling (NMDS) (NMDS axes 1 and 2) ordination graphs of small mammal species capture composition (stress = 0.14), showing the convex hull polygon for season (left) and year (right). Point fill color is average lux.

PERMANOVA supported these observations, suggesting a significant influence of season (Pseudo $F = 1.465$, $p = 0.011$) and a trend for year (Pseudo $F = 1.414$, $p = 0.056$) (*Table 2.4*). The explanatory variables of type of light technology, light intensity (lux), canopy cover (gap fraction), and reach were removed from the model due to violating assumptions of dispersion. Since all explanatory variables associated with ALAN violated dispersion assumptions within this model, the influence that ALAN has on these small mammal captures is not able to be analyzed using PERMANOVA.

Table 2.4: PERMANOVA partitioning and analysis of small mammal capture data, based on square root transformed captures and Bray – Curtis dissimilarities. Pseudo F statistics were calculated for each term by comparing to univariate expectations of mean squares; *p*-values were obtained using 9999 permutations under a reduced model. Significance($p < 0.05$) is indicated with (*) and trends ($p > 0.05$ and <0.10.1) are indicated with (^).

Source	*df*	*SS*	R^2	Pseudo *F*	*p*
Year	1	0.689	0.028	1.414	0.056^
D50	1	0.558	0.022	1.144	0.250
Impervious Surface Distance	1	0.524	0.021	1.074	0.201
Season	1	0.714	0.029	1.465	0.011*
Residual	46	22.429	0.903	-	-
Total	50	24.830	1.000	-	-

Results from the NMDS comparing the influence of season and reach on total mammal camera-trap encounter compositions (*Figure 2.8*) suggest potential seasonal differences in total mammal encounter composition, but no difference by ALAN.

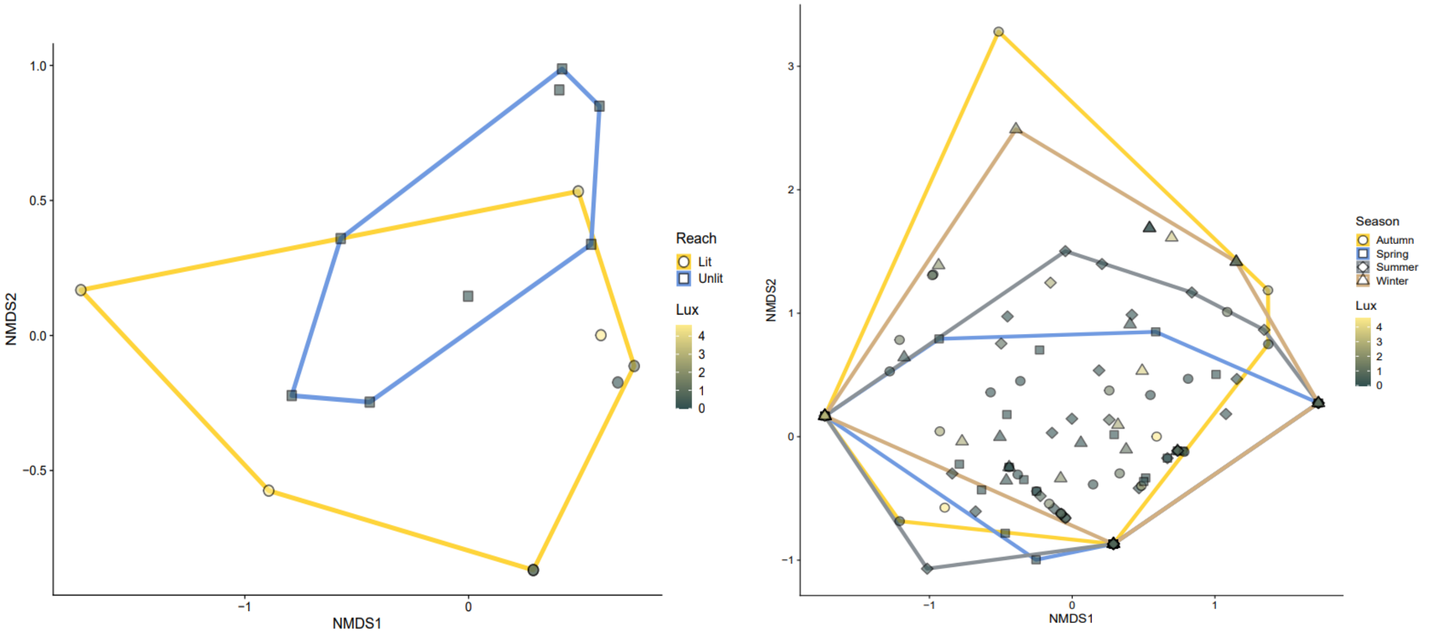


Figure 2.8: 2-D nonmetric multidimensional scaling (NMDS) (NMDS axes 1 and 2) ordination graphs of species camera encounter composition (stress = 0.14), showing the convex hull polygon for reach (left) and seasons (right). Point fill color is average lux.

PERMANOVA supported these observations, suggesting a significant influence of time of day (Pseudo $F = 5.486$, $p = 0.000$) and season (Pseudo $F = 1.26$, $p = 0.002$), but no influence by reach (Pseudo $F = 1.097$, $p = 0.388$) (*Table 2.5*). The explanatory variables of type of light technology, light intensity (lux), and canopy cover (gap fraction) were removed from the model due to violating assumptions of dispersion.

Table 2.5: PERMANOVA partitioning and analysis of mammal camera trap encounter data, based on square root transformed encounters and Bray – Curtis dissimilarities. Pseudo F statistics were calculated for each term by comparing to univariate expectations of mean squares; p-values were obtained using 9999 permutations under a reduced model. Significant p-values ($\alpha = 0.05$) are indicated with (*).

Source	*df*	*SS*	R^2	Pseudo *F*	*p*
Time of Day	1	9.213	0.037	5.486	0.000*
Reach	1	1.843	0.007	1.097	0.388
D50	1	1.88	0.008	1.12	0.163
Impervious Surface Distance	1	2.282	0.009	1.359	0.326
Season	3	6.347	0.026	1.26	0.002*
Residual	134	225.019	0.913	-	-
Total	141	246.558	1	-	-

Results from the NMDS comparing the influence of time of day and season on mammal guild camera-trap encounter compositions (*Figure 2.9*) suggest potential daily and seasonal differences in mammal guild encounter compositions, but no difference by ALAN.

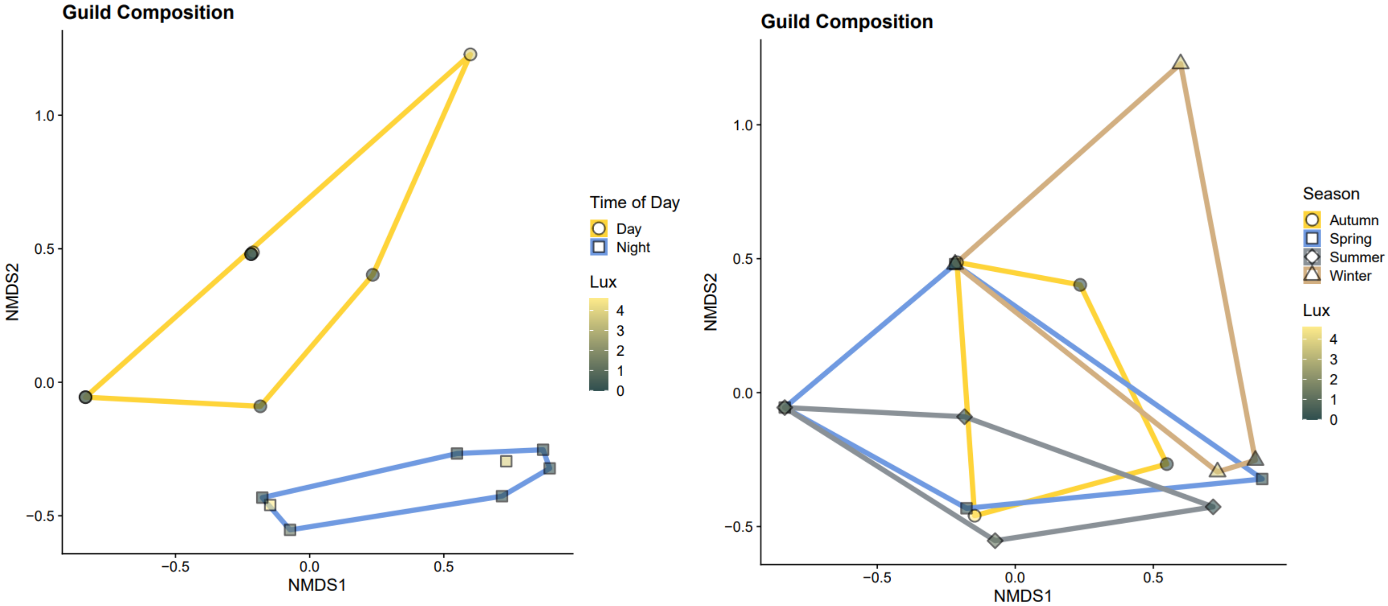


Figure 2.9: 2-D nonmetric multidimensional scaling (NMDS) (NMDS axes 1 and 2) ordination graphs of guild camera encounter composition (stress=0.09), showing the convex hull polygon for time of day (left) and seasons (right). Points are sites with fill color of average lux.

PERMANOVA supported these observations, suggesting a significant influence of time of day (Pseudo $F = 4.521$, $p = 0.000$) and season (Pseudo $F = 1.252$, $p = 0.000$), but no influence by reach (Pseudo $F = 1.063$, $p = 0.407$) (*Table 2.6*). The explanatory variables of type of light technology, light intensity (lux), and canopy cover (gap fraction) were removed from the model due to violating assumptions of dispersion.

Table 2.6: PERMANOVA partitioning and analysis of mammal guild camera trap data, based on square root transformed encounters and Bray – Curtis dissimilarities. Pseudo F statistics were calculated for each term by comparing to univariate expectations of mean squares; p-values were obtained using 9999 permutations under a reduced model. Significant p-values (α = 0.05) are indicated with (*).

Source	*df*	*SS*	R^2	Pseudo *F*	*p*
Time of Day	1	8.648	0.031	4.521	0.000*
Reach	1	2.033	0.007	1.063	0.407

Continued

Table 2.6 Continued

D50	1	2.181	0.008	1.140	0.192
Impervious Surface Distance	1	2.547	0.009	1.331	0.243
Season	3	7.185	0.026	1.252	0.000*
Residual	134	256.329	0.919	-	-
Total	141	278.917	1.000	-	-

Discussion

In the riparian areas of low-order streams in the Columbus Metropolitan Area, we did not find evidence that ALAN influenced mammal diversity or community composition. There were no differences between individual species or guild encounters at lit reaches compared to unlit reaches. Mammal communities are often influenced by seasons, which is a response that has been seen in small mammal (Grant and Birney 1979) and large mammal communities (Western 1975). Small mammal communities in disturbed landscapes (i.e., agriculture fields) are still mediated by seasons (Benedek and Sîrbu 2018) while the occupancy of medium- and large-bodied mammals in anthropogenically-disturbed environments is seasonally dependent (Ehlers Smith et al. 2018). Seasonality influenced the mammal community response at across levels of our study, regardless of ALAN presence. Year also may have had an influence on the small mammal community, which is supported by other studies of small mammals that show precipitation and resource differences between years have strong influences on small mammal communities (Wolff 1996). More recently, studies have shown that even when faced with massive habitat transformations, community compositions still varied widely from year to year (Chapman et al. 2018). Time of day appeared to influence mammal guild and medium- and large-mammal community compositions. Most rodents and small carnivores, all bats, and about 80% of marsupials are nocturnal while other mammals also have strict times of day where they are active (Walls 1942). While mammals often maintain their daily activity patterns even when overlapping other species (Mori et al. 2019), some mammals exposed to stressors can adjust their daily activity patterns (Diao et al. 2021).

There was no evidence that any of the measures of ALAN (reach, light intensity, light technology) influenced total mammal encounters or species richness. Sediment size (D50) was positively correlated with total encounters and species richness. One possible reason sediment size influenced encounters and species richness is that sediment size can act as a proxy for stream size, with larger sediment size being associated with larger stream systems (Vannote et al.

1980, Whiting and Bradley 1993). However, the measure of distance to nearest impervious surface, which was a measure of both urbanization and riparian width, was not correlated with encounters or species richness. Another possible reason is larger sediment size allows smaller mammals to traverse and utilize the stream. Camera trap observations of squirrels, chipmunks, mice, weasels, and other small mammals at the sites showed them often using cobble and boulders to cross the streams, with larger sediment size possibly acting as connectors for small mammals to move between banks. Increasing habitat connectivity could explain higher encounters and species richness because greater habitat connectivity is associated with greater biodiversity (reviewed in Correa Ayram et al. 2016). Another possible reason that sediment size could be correlated with encounters and species richness is that sediment size could be serving as an indicator for site urbanization. More urbanized streams are often associated with smaller sediment sizes through greater erosion and sediment discharge (Hogg and Norris 1991, Walters et al. 2003). Since greater degrees of urbanization are associated with reduced mammal species richness (Mackin-Rogalska et al. 1988), sediment size acting as a proxy for urbanization could be why we are seeing this correlation but further research is needed.

We hypothesized that ALAN would decrease encounters and change mammal community compositions in all three levels, which was not supported by any of the data. A possible explanation could be that urban mammals are already well adapted to anthropogenic stressors (Gallo et al. 2017) and are less likely to be disrupted by ALAN. Studies on urban mammals show they will often utilize resources and anthropogenic disturbances to their advantage (e.g., Gehrt et al. 2013, Gallo et al. 2017), meaning that the presence of ALAN may not be impacting their habitat selection and movement behavior. Most of the species encountered in this study are considered urban-exploiters such as white-tail deer and raccoons (Gehrt et al. 2013), meaning they easily adapt and take advantage of urban environments. Lack of differences in encounters could indicate that responses to ALAN is another example of the resiliency of urban-exploiters and their ability to adapt and take advantage of areas that urban-avoiders cannot. A caveat to this is that red foxes were placed in the large predator guild due to their ability to consume to a larger array of prey species. However, based on their body size, they can be shift to the small predator guild to be included with species more consistent with their body sizes.

We also hypothesized that increased light intensity would decrease mammal encounters and diversity but we did not find strong evidence indicating the light intensity influenced either response variable. At least to some extent, we attribute the lack of influence of ALAN to the relatively low intensity at our study sites. The highest average lux observed at any of the lit reaches was <3 lux. In other studies that have showed changes to mammal movement patterns, lux values that influenced these behaviors were >150 lux, with the low treatment in that study still being 15× greater in lux values than our site with the greatest lux value (Bliss-Ketchum et al. 2016). A similar study saw changes in mammal movement patterns at 27 lux (de Molenaar et al. 2003) while other ALAN studies in urban settings have seen changes in ecological patterns in the range of 5-3,000 lux (Ohlberger et al. 2008, Yorzinski et al. 2015, Sullivan et al. 2019). Our findings of no differences at low lux levels could be used in the development of road lighting thresholds with the knowledge that < 4 lux did not elicit habitat-use responses by mammals.

We also hypothesized that any trends in mammal community composition, encounters, or species richness would have greater correlation at lit reaches with LED lights compared to HPS lights. None of the data supported this hypothesis. Deer exhibit different electroretinography (ERG) responses to multiple light wavelengths (Crivelaro et al. 2018), indicating different light wavelengths from ALAN should change their responses. Mice can observe and respond to some wavelengths of UV light (Peirson et al. 2018) while some bats exhibit positive phototaxis to green light (Voigt et al. 2017) and red light but not to white light (Voigt et al. 2018). Mammals being influenced by different wavelengths of light indicates that light technologies with different spectral ranges should show a difference in mammal communities, but the data does not support that. No differences based on light technology could be due to the increasing prevalence of LED lighting in urban areas where they are often becoming the standard lighting choice because of their brightness and energy saving qualities (Longcore et al. 2015). It is possible that urban mammals are not affected by LED night lighting since they are exposed to it more often. Since white LED lights have such a broad emittance spectrum that encompasses the entire spectrum that HPS lights emit (Davies et al. 2017), mammals that are not being impacted by LED lights would most likely not be impacted by HPS lights either.

Potential Mechanisms

One potential driver for the lack of differences in mammal space usage and community composition in these riparian areas is the size and light intensity of the ALAN-impacted areas. The study reaches were limited to 30 meters because that was the extent that the artificial light extended into the canopied streams. Streetlights can emit light at 30 lux at ground level directly beneath them, but those lux values are reduced to 2 lux at 20 meters away from the light source (Bennie et al. 2016). This reduction is increased by the tree canopy and other vegetation preventing high light intensity levels from reaching the floor of the riparian zone in a large area. With mammals native to Ohio being able to travel 1.6 km (Murie 1963) to up to 18.6 km (Nelson et al. 2004) in a single day, the short distance of light infiltration may not be large enough to impact mammal movement and space usage behavior. The smallest home range of any observed mammal in this study is 590m^2 [*Peromyscus leucopus*;(Wolff 1985)], meaning the area of light infiltration observed at our sites was still less than half of their home range and a smaller percentage for the other species. As noted above, other studies that observed differences in mammals moving through and utilizing areas that had experimentally adjusted lux values that were much higher than the ones that we observed (Bliss-Ketchum et al. 2016). While our observed light intensity (0.28-3.0 lux) is noticeably greater than typical nighttime lighting with no ALAN present (full moon = 0.1 lux), it is up to 50x lower than other ALAN studies. It is possible that there were no differences in the mammal community because the size and intensity of ALAN impacts that are present along these streams in Columbus, OH are not large enough to elicit a response.

Another potential driver of the lack of differences observed is the importance of riparian areas to urban mammals. Riparian forests provide food, water, and refugia to multiple species of mammals that are often limited in urban areas (Dickman 1987, Mahan and O’Connell 2005). Riparian areas can often be the only way mammals can safely move across a fragmented urban landscape (Hilty and Merenlender 2004). With these riparian zones being so important for sustaining urban mammal populations, ALAN impacting these areas may not be enough to deter mammals from utilizing them.

Finally, a potential driver of no differences between lit and unlit reaches is all experimental sites being urban sites. ALAN is often correlated with other urbanization impacts like increased impervious surface cover, low vegetation cover, and reduction of available ecological resources to name a few (Blair and Launer 1997, Rich and Longcore 2013). With all experimental sites in this project being located within the urban center, the mammals living there are already experiencing multiple anthropologic disturbances and are more tolerant to them (McCleery 2010). More tolerant communities are composed of more urban-exploiters and are less likely to be impacted by ALAN, so the impacts of ALAN may have been masked by other urban stressors. Another perspective is this shows that ALAN may be another urban stressor that urban-exploiters can resist to be able to use niches that other species cannot (Gehrt et al. 2013).

Conclusions

Artificial light at night will continue to grow as an environmental stressor as humans continue to urbanize and expand. Urban expansion increased by 58,000 km^2 between 1970 and 2000 and that trend is expected to increase, with estimates of an increase between 430,000 km^2 to 12,568,000 km^2 in urban land cover from 2010 to 2030 (Seto et al. 2011). This rapid increase in urban areas will bring with it an increase in areas impacted by ALAN. Most previous ALAN studies on mammals have used experimentally increased light levels to elicit measurable responses (Stone et al. 2015b, Bliss-Ketchum et al. 2016, Shier et al. 2020). For example, Bliss-Ketchum et al. (2016) increased nighttime lux levels to ~150 lux to change movement responses in some mammals. Here, we provide insight into how mammal communities that use riparian areas in an urban center are impacted by ALAN under light intensity representative of urban streams with riparian buffers. We found no differences in mammal communities found at stream reaches with and without ALAN, with the same trend observed in total mammal observations and species richness metrics. These results are important to consider as increased urbanization will lead to a greater proportion of mammals being exposed to ALAN (Rich and Longcore 2013).

Our results should be considered in the broader context of other studies that show that ALAN can negatively impact mammal movement behavior (Bliss-Ketchum et al. 2016) and change food-web interactions between aquatic and terrestrial systems (Sullivan et al. 2019) that could lead to changes in the mammal communities in these riparian systems. While we did not observe overall changes to mammal communities under ALAN, these potential mechanisms should be studied under similar lighting conditions to understand if they are still being impacted under ALAN. This study focused on behavioral changes, but mammals' physiology (Vriend and Lauber 1973) and reproduction potential (Robert et al. 2015) can also be impacted by ALAN and those factors should be addressed in urban riparian mammal communities. Identifying potential ALAN ecological thresholds has also been identified as an important priority (Longcore and Rich 2004, Rich and Longcore 2013), and our results could contribute to this effort. Where possible, future studies into ALAN impacts of riparian mammals should experimentally increase the area of light impact and the light intensity to see if greater ALAN area or intensity would have negative impacts. Specifically, studies that increase the area of ALAN impact to entire home ranges of mammals would be important to understand space usage and movement. Additionally, studies could remove daytime encounters to see if presence of artificial light shows changes in mammal communities. Also, investigations outside of urban areas that can better isolate the impacts of ALAN from the suite of urban stream stressors [i.e., elevated nutrients and contaminants, altered stream morphology, increased dominance of tolerant species (Paul and Meyer 2001)] will be important.

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Chapter 3: *Peromyscus* Diet Reflects Small Shifts in Aquatically-based Nutritional Subsidies under Artificial Lighting at Night

Abstract

Artificial light at night (ALAN) is an expanding environmental stressor under global increases in urbanization. ALAN has been shown to impact aquatically-derived energy in terrestrial arthropods and feeding behavior in small mammals. However, there is limited knowledge of potential impacts of ALAN on aquatically-derived energy assimilated by riparian small mammals. We investigated the impacts of ALAN (0.1-2.5 lux) on riparian small mammal trophic interactions along 12 urban headwater streams in Columbus, Ohio, USA. ALAN presence was related to the proportion of energy derived from aquatic vs. terrestrial primary producer pathways in the genus *Peromyscus*, the only small mammals with enough samples to estimate diet proportions. At lit reaches, Peromyscus nutritional subsidies derived from aquatic primary producer pathways that originate from stream periphyton were 1.2% lower than at unlit reaches. Canopy cover was also associated with the proportion of energy derived from a terrestrial primary producer pathway that is indirectly consumed by *Peromyscus* (i.e., originating from aquatic detritus). Site as a random effect in linear-mixed models explained the greatest amount of variation in the proportion of energy derived from different primary producer pathways. Overall, we found evidence that ALAN was associated with changes in small mammal trophic interactions, but only by small amounts (>2% change in diet). These results suggest that, at the lighting levels of this study, aquatic-terrestrial trophic interactions are only slightly impacted by ALAN, which can be used to develop roadway lighting thresholds.

Introduction

Artificial lighting at night (ALAN) is a growing environmental stressor that is linked to the expansion of urban areas (Utzinger and Keiser 2006, Rich and Longcore 2013). Artificial light pollution can refer to astronomical light pollution, which is light that disrupts the visibility of the night sky, the effectiveness of telescopes, and interferes with satellite imagery (Cinzano et al. 2001, Longcore and Rich 2004). However, downwelling ALAN also can impact ecological processes, known as ecological light pollution (Longcore and Rich 2004). ALAN has been observed to influence a suite of organisms and ecological processes: e.g., the photoperiod response in plants (Bennie et al. 2016), physiology of mice (Vriend and Lauber 1973), and aquatic-terrestrial energy fluxes in invertebrate communities (Sullivan et al. 2019). Although there are a growing number of ALAN studies addressing the ecological impacts at the community or ecosystem level (Sanders and Gaston 2018, Zapata et al. 2019), most investigations have focused on individual or population level.

Historically, human settlements have occurred along rivers and streams. With increasing modernization, urbanization, and sprawl of these settlements, riparian areas have experienced greater ALAN exposure compared to other systems (Kummu et al. 2011). Riparian areas are used for both cover and food resources by urban mammals (Mahan and O'Connell 2005), which can take advantage of aquatic-energy subsidies and use these areas to as movement corridors through cities (Hilty and Merenlender 2004). For example, Kautza and Sullivan (2016) found that terrestrial mammals can derive a large proportion of their diet from aquatic sources. Raccoons (*Procyon lotor*) along the Scioto River in Columbus, Ohio, derived 48% of their energy from aquatic primary producer sources.

Small mammals are an abundant and important part of the mammal assemblage within urban riparian areas (McCleery 2010). Small mammals are small-bodied species, excluding bats, with a body weight less <1 kg (Kennerley et al. 2021). Small mammals play an important role in multiple ecological processes including seed dispersal, soil dynamics, nutrient cycling, pollination, and habitat maintenance due to their functional and morphological diversity (Whitford and Kay 1999, Clark et al. 2016, Zoeller at el. 2016, Campos et al. 2017). Despite their ecological importance, there have been fewer studies done on conservation research of small mammals compared to larger and more charismatic species (Kennerley et al. 2018).

Since small mammals are functionally and morphologically diverse, they can be used as bioindicators of habitat condition. For example, Romañach et al. (2020) measured abundances and captures of small mammals at both unrestored and restored Florida wetlands. They found higher abundance and capture rates of cotton mice (*Peromyscus gossypinus*) and marsh rice rats (*Oryzomys palustris*) were more prevalent in wetlands that had already been restored compared to wetlands that had not. Pearce and Venier (2005) studied small mammal responses to clear cutting in boreal forests. They found that red-backed voles (*Clethrionomys gapperi*), an herbivorous rodent that is active all day, were less abundant in clear-cut areas. However, deer mice (*Peromyscus maniculatus*), a small mammal generalist that is typically nocturnal, was positively related to recently clear-cut forests.

Small mammals have also exhibited responses to ALAN. Vriend and Lauber (1973) found that artificial lighting disrupts the physiology of deer mice. The presence of artificial light, and specifically at higher intensities, was associated with higher with higher total body, testes, and spleen weights while testes and spleen weights were greatest under red light wavelengths. Studying impacts of ALAN at under-road passage structures, Bliss-Ketchum et al. (2016) found a decrease in the frequency of deer mice track paths in lit passages (~150 lux) compared to ambient passages. ALAN was also shown to impact foraging behavior in small mammals. Shier et al. (2020) found that kangaroo rats (*Dipodomys stephensi*) avoided foraging patches under ALAN produced by a 756 lumen LED light. This avoidance occurred at both low- and high-quality foraging patches with ALAN, and the researchers implicated predator avoidance as a likely mechanism.

ALAN can disrupt food-web interactions in multiple ways. Bats adjust their feeding behavior and take advantage of the "vacuum cleaner" effect of streetlights to consume greater proportions of invertebrates at one time (Rydell 1992). ALAN can disrupt food-web subsidies between aquatic and terrestrial systems. For instance, Meyer and Sullivan (2013) found a decrease in body size and family richness in emergent aquatic insects, and with that a decrease in tetragnathid spider density which feed almost exclusively on emergent invertebrates. Sullivan et al. (2019) found that different artificial light levels altered food-chain length and reliance on aquatically-derived energy (i.e., pathways originating from aquatic primary producers) by terrestrial arthropods. Under moderate light levels (0.6-2.0 lux), there was a decrease in food-chain length and reliance on aquatically-derived energy, but the amount of aquatic energy contributions increased again under greater light intensity (2.1-4.0 lux).

We compared the reliance on aquatically-derived energy sources (i.e., nutritional subsidies originating from aquatic periphyton) and the trophic position of small mammals between stream reaches with and without ALAN. We hypothesized that the presence of ALAN would reduce small mammal reliance on aquatically-derived energy sources due to reductions in emergent aquatic insect densities. Second, we anticipated that trophic position would decrease under ALAN due to reduced invertebrate densities, causing small mammals to consume more terrestrial basal resources directly. Thirdly, we hypothesized that the decrease in reliance on aquatically-derived energy sources and trophic position would be more pronounced under higher ALAN intensities due to a greater reduction in emergent aquatic insect abundances from greater aquatic predation success and reduced emergent insect survival. We explored the influences of stream geomorphic features, vegetation characteristics, and urbanization variables as potential mechanisms linked to changes in diet proportions and trophic position of small mammals.

Methods

Study Sites

The Columbus Metropolitan Area (hereafter CMA) spans 8,208 km^2 in central Ohio with a population of 2.4 million people. The CMA is in the Scioto River Watershed and is characterized by the Scioto River flowing through it. The Scioto River is a 6th-order tributary of the Ohio River that drains a 16,882-km^2 basin throughout Ohio (Reick and Sullivan 2020). The upper section of the basin where the Scioto River flows through Columbus, is mostly row-crop agriculture north of the city and suburban/urban land use moving towards the city (Nelson 2014). Ten paired lit-unlit 1st-3rd order stream-riparian sites were selected for our study, based on previous knowledge of the system (Sullivan et al. 2016, Sullivan et al. 2019, Rieck and Sullivan 2020) and synoptic surveys of ALAN intrusion into riparian zones (Figure 2.1). The following criteria were used in site selection: light source (streetlights, house lights, yard lights, etc.) was present over a 30 m stretch of a stream (i.e., lit reach), light intensity at night over the lit reach averaged between 0.28 and 3.5 lux (typical light intensity values for canopied streams in the CMA were 0.01-4.0 lux, Sullivan et al. 2019); upstream from the lit reach was an unlit 30-m reach of the same stream with similar geomorphic, terrestrial vegetation, and flow features (Figure 2.2); upstream reach was not impacted by ALAN; there were no barriers (e.g., artificial flow obstructions, bridges) or additional water inputs (e.g., drainage pipes, tributaries) between the two paired study reaches. Two additional sites (i.e., two paired unlit-unlit) - one within the CMA and one was in a rural area 70 km northwest of Columbus to avoid urban impacts – served as reference sites. Unlit reaches were always located upstream from lit reaches to prevent downstream flow impacts from lit reaches being recorded at unlit reaches. Pictures of sites and reaches are available (Appendix A)

Hair Samples

To characterize the riparian small mammal food web, samples were taken from primary and secondary consumers (macroinvertebrates and small mammals, respectively) and their hypothesized major food sources (*Figure 3.1*). We collected hair samples of small mammals and whole tissue samples (entire macroinvertebrate, plant clipping, algae scraping) were sampled as basal resources.

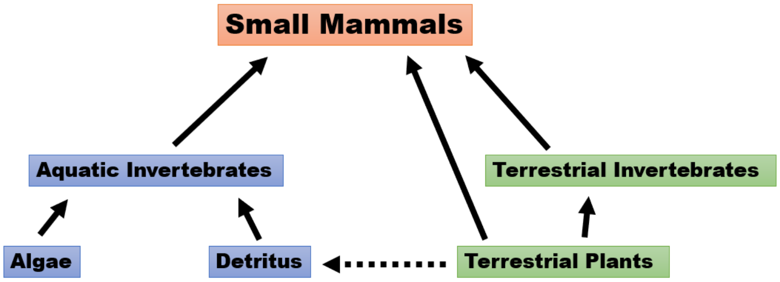


Figure 3.1: A conceptual overview of the study food web. Riparian small mammals consume aquatically-derived subsidies from emergent aquatic invertebrates and terrestrially-derived subsidies from both terrestrial plants and invertebrates. The detrital pathway shows that consuming aquatic invertebrates could result in deriving energy from both aquatic and terrestrial basal resources.

Small mammals were trapped using Sherman live traps (7.62 cm x 8.89 cm x 22.86 cm, galvanized steel doors and treadle; H.B. Sherman Traps, Tallahassee, Florida, USA) in a paired transect design per reach (Pearson and Ruggiero 2003). Each transect contained seven pairs of traps (14 total), with each pair of traps spaced 5 m apart and 5 m from other pairs. Trapping transects were opened for three consecutive nights at each reach, with the lit and unlit reach of each paired study site being trapped concurrently. Traps were baited with a mixture of oats and peanut butter inside of bait capsules. The capsules were made of electrical conduit wrapped in hardware cloth designed to prevent small mammals from consuming the bait and potentially impacting their isotopic signature..

Trapping occurred from August 2020 to August 2021, with each site being sampled twice: once from August-October 2020 and once from June-August 2021. All captured small mammals were placed in handling bags to reduce stress (Sikes et al. 2011). All captures were identified to species with identifications based on guidelines from Gottschang (1981). A sample of guard hairs was taken from the rear of each captured mammal. Ear tags (1005-1 Ear Tags, National Tag and Band Company International Identification Inc., Newport, KY, USA) were attached to all captured individuals to identify if individuals had already been sampled. All captured small mammals were released at the same place they were captured. Hair samples were frozen until lab processing. Our sampling methods concerning vertebrates conformed to the standards set by the OSU Institutional Animal Care and Use Committee (IACUC, Protocol 2010A0003-R3).

Aquatic Sources

Periphyton samples were collected as aquatic basal resources during June-July 2020 and January-February 2021. Periphyton was sampled by collecting six rocks per transect through random selection from the stream. A 5 cm x 5 cm square of periphyton was scrubbed off each rock at all reaches. Periphyton was stored in 50-mL Falcon tubes and frozen until lab processing.

Emergent invertebrates were collected as primary consumers of aquatic sources during July 2020. They were collected by placing one 1-m^2 floating Mundie-style emergent trap (Mundie 1964) at each reach (two per site). Traps were placed for 10 days following Meyer and Sullivan (2013), with invertebrates being collected from traps every five days to avoid sample loss from possible flooding/loss of trap. Following collection, emergent invertebrates were stored in 70% ethanol until sorting and in-lab identification. Emergent invertebrates were combined into a single composite sample per reach. The composite sampled consisted of relative proportions of emergent invertebrate species captured. Samples were rinsed and dried to remove excess ethanol.

Terrestrial Sources

To characterize basal food resources, we collected terrestrial vegetation during August-September 2020 and June-August 2021 and stream detritus samples during August-September 2019, January-February 2020, August-September 2020, and January-February 2021. Clippings of the most common plant tissues (grass, forb, rush, tree fruits/nuts, etc.) were collected at each reach. For woody species that are not directly consumed by small mammals, any fruits or nuts they produced were collected instead. Benthic detritus was collected through the random selection of five leaves in each reach. All vegetation samples were placed in whirlpacks and frozen until lab processing.

We collected terrestrial macroinvertebrates during August-September 2020. Terrestrial macroinvertebrates were sampled using two different methods: 25 cm x 25-cm ramp pitfall traps (Bouchard et al. 2000) and 40 cm x 400-cm hay-bait traps (Tuf et al. 2015). Three ramp traps were placed at each reach (one at the top, middle, and bottom of the reach) for three days. Macroinvertebrates from ramp traps were collected each morning to prevent sample loss through predation. Two hay-bait traps were placed at each reach (one at the top and bottom of the reach) for 10 days. In lieu of hay, detritus from the stream was used to cover the trap to prevent isotopic contamination of the food web from introducing hay. The hay-bait traps were collected after 10 days and picked through in the field. The ramp traps were used to collect mobile terrestrial macroinvertebrates while the hay-bait traps collected ground-dwelling macroinvertebrates. All terrestrial macroinvertebrates were placed in vials with 70% ethanol until in-lab identification. Terrestrial macroinvertebrates were identified to family using Borror and White (1970). All individuals from the three most abundant families at each reach were analyzed for isotopic signature, with each family making a composite sample. All samples were rinsed and dried to remove excess ethanol.

Stable Isotope Analysis

Studying food-web interactions is important for understanding how communities and ecosystem's function (Post et al. 2000). One way to understand food web linkages is by using naturally abundant stable isotopes to estimate relative diet proportions and trophic feeding position of organisms (Kling et al. 1992). To understand complex trophic interactions, two stable isotopes are commonly used: ^{13}C and ^{15}N. Because $\delta^{13}C$ varies little with trophic position but greatly between primary producers (Post 2002), $\delta^{13}C$ in consumer tissue can be used to determine basal resource pathways from which an organism derives its energy (DeNiro and Epstein 1978, Post 2002). The $\delta^{15}N$ in consumer tissue can be used to estimate relative trophic position because $\delta^{15}N$ shows consistent enrichment as trophic level increases (DeNiro and Epstein 1981).

For stable isotope analysis, mammal hair, macroinvertebrate (terrestrial and emergent), terrestrial vegetation, detritus, and periphyton samples were oven dried (60°C, 48 h) and homogenized using a ball mill grinder. Homogenized samples were packed into tin capsules. Tissue from multiple macroinvertebrates and vegetation classes within the same group were combined into a composite sample to reduce variation (Lancaster and Waldron 2001).

Stable isotope samples were analyzed for carbon (C) and nitrogen (N) using elemental analysis isotope ratio mass spectrometry (EA-IRMS) at the Washington State University Stable Isotope Core (Pullman, Washington, USA) and the Southern Methodist University Stable Isotope Laboratory (Dallas, Texas, USA). Stable isotope results are reported in δ notation.

$$\delta X(‰) = \left(R_{sample}/R_{standard} - 1\right) \times 1{,}000$$

Where X is ^{13}C or ^{15}N and R is $^{13}C/^{12}C$ or $^{15}N/^{14}N$. C values are expressed relative to Vienna Pee Dee Belemnite and N values are expressed relative to atmospheric air (N_2).

Environmental Variables

Light illuminance (lux) was measured at three transects (0m, 15m, 30m), two positions (left-middle, right-middle), and three heights (1cm below water surface, 1cm above surface, 1 m above surface) using an ILR 1700 Radiometer with a waterproof illuminance (lx) sensor (SUD033/Y/W; International Light Technologies, Peabody, Massachusetts). Spectral composition of primary light sources was recorded using an Ocean Optics® Flame UV-VIS Spectrometer (Ocean Insight, Orlando, Florida). Light sources at each site were categorized as either high-pressure sodium (HPS) or light-emitting diode (LED) based on spectral distribution. Illumination and spectrum were measured at each reach during summer 2019, autumn 2019, winter 2020, summer 2020, autumn 2020, and winter 2021 at least two hours.

Canopy cover was measured from canopy photographs photographed with a fish-eye lens camera during sampling periods in 2019, 2020, and 2021. To quantify urbanization of each reach, impervious surface distance (the shortest distance from the stream to an impervious surface) was measured was measured four times at 10-meter increments along each reach using the "Measure" function in ArcGIS Pro (ESRI 2019). Following Wolman (1954), sediment size was measured using a gravelometer at the top, middle, and bottom of each reach by completing pebble counts with a minimum of 75 pebbles to estimate the median sediment size (D_{50}) during Spring 2021.

Statistical Analysis

The proportion of diet contributions of each basal resource for the different small mammals was estimated using Bayesian mixing models in the **MixSIAR** package in R (Stock and Semmens 2016, R Core Team 2018).

$$source + discrimination\ SD = \sqrt{\sigma_{source}^2 + \sigma_{discr}^2}$$

Where σ_{source}^2 is the standard deviation of the source value and σ_{discr}^2 is the standard deviation of the discrimination factor for that source.

Uninformative priors were used for the mixing model. The **MixSIAR** package uses Markov Chain Monte Carlo (MCMC) methods to estimate diet proportions of different basal resources.

Gelman-Rubin and Geweke tests were the diagnostic tests used to confirm convergence. For the Gelman-Rubin test, the model was considered converged if all the Gelman diagnostics were <1.1 (Gelman et al. 2013). For the Geweke test, the model was considered converged if all three chains had less than 5% of the Geweke diagnostic (z-scores) were outside of ±1.96 from the mean estimate (Geweke 1992).

Trophic position (TP) was estimated for individuals based on the estimated diet proportions of terrestrial vs. aquatic basal resources. TP is a quantitative measure of vertical location within a food web and was estimated using the equation in Post (2002).

$$TP = 1 + [\delta^{15}N_c - \alpha\delta^{15}N_{base1} - (1-\alpha)\delta^{15}N_{base2}]/\Delta_N$$

Where *c* is the consumers (e.g., *Peromyscus*, *Blarina brevicauda*, etc.), N_{base1} is the periphyton collected from sediment in the stream, N_{base2} is the detritus and terrestrial vegetation, Δ_N is the trophic fractionation for $\delta^{15}N$ for each trophic level (i.e., 3.4‰, Post 2002), and α is an estimate of N derived from the periphyton. I utilized the diet proportion estimations from the Bayesian mixing model as α.

For each of the diet proportions as well as the estimated trophic position, groups were compared at lit versus unlit reaches using paired t-tests (*t*) with $\alpha = 0.05$.

Linear mixed-effect models (LMMs) were used to assess differences in TP and diet proportions of different basal resources between reaches. Season, time of day, light technology, impervious surface, sediment size (D50), and reach were included as fixed effects in the models. We ran two regression models: one looking at the effects of light presence/absence and another the effects of light intensity. Site was included as the random effect.

The amount of variation explained by site (the random effect) in the LMMs is the difference between the total variation of the model (Conditional R^2) and the variation of the model explained by fixed effects (Marginal R^2).

$$R^2_{Random\ effects} = R^2_{Conditional} - R^2_{Marginal}$$

All data analysis was completed in R (R Core Team 2018) using base packages, the **MixSIAR** package, and the **vegan** package (Dixon and Palmer 2003). In all statistical tests, an $\alpha = 0.05$ ($p < 0.05$) was used to indicate statistical significance; an $\alpha = 0.10$ ($p < 0.10$) was used to indicate a trend.

Results

The two types of lighting found at the different sites were high pressure sodium (HPS) and light emitting diode (LED) lights. There were significant differences in average lux values at night between lit and unlit reaches at the same sites (*Figure 2.3*). Average lux values at lit reaches ranged from 0.28-3.5 lux (*Figure 2.4*).

Isotopic Composition

A total of 117 hair samples were collected from five different species of small mammals. A majority (104, 89%) were from the genus *Peromyscus*, which has two different species in Ohio: white-footed mice (*Peromyscus leucopus*) and deer mice (*Peromyscus maniculatus*). Due to their similarities in body structure, color, and other identifying features that make it difficult to identify to species in the field (especially in juvenile/sub-adult individuals), as well as their similarities in average diet, both species were combined in analysis. The average $\delta^{13}C$ for *Peromyscus* was similar between lit vs unlit reaches and seasons (*Table 3.1,* Appendix E). Due to the small numbers of captures of short-tailed shrews (*Blarina* brevicauda), eastern chipmunks (*Tamias striatus*), and Virginia opossums (*Didelphis virginiana*), we removed these species from any diet proportion calculations and linear mixed-effect modeling. Using *Peromyscus* as our study species was valid due to them being the most abundant small mammal in Ohio and their generalist feeding strategy that allows them to take in the most abundant food sources and switch food sources under environmental pressures (Gottschang 1981).

Table 3.1: Summary statistics for small mammal and basal resources δ^{13}C ‰ (per mill relative to Vienna Peedee Belemnite x 1000) at experimental sites by sampling period and reach, including minima (Min), medians, maxima (Max), mean, and standard deviation (SD).

		δ^{13}C (‰)									
		Lit Reaches					Unlit Reaches				
		Min	Median	Max	Mean	SD	Min	Median	Max	Mean	SD
Biotic Variable	Season										
Small Mammals											
Peromyscus spp.	Fall 2020	-25.86	-23.66	-22.07	-23.78	1.08	-26.83	-23.34	-19.79	-23.29	1.61
	Summer 2021	-24.7	-23.2	-19.8	-22.98	1.23	-25.2	-23.45	-20.9	-23.47	1.03
Blarina brevicauda	Fall 2020	-26.37	-26.37	-26.37	-26.37	0.00	-	-	-	-	-
	Summer 2021	-24.1	-24.1	-24.1	-24.1	0.00	-	-	-	-	-
Tamias striatus	Fall 2020	-23.17	-23.17	-23.17	-23.17	0.00	-	-	-	-	-
	Summer 2021	-23.8	-23.05	-22.5	-23.07	0.46	-21.6	-21.6	-21.6	-21.6	0.00
Didelphis virginiana	Summer 2021	-22.40	-22.40	-22.40	-22.40	0.00	-	-	-	-	-
Aquatic Basal Sources											
Periphyton	Summer 2020	-30.76	-26.81	-7.43	-26.13	4.64	-32.76	-26.65	-16.43	-26.27	3.93
	Winter 2021	-32.71	-25.22	-17.60	-24.91	4.54	-32.41	-25.76	-16.86	-25.26	4.26
Terrestrial Basal Sources											
Forb	Fall 2020	-34.57	-33.02	-28.93	-32.60	1.66	-35.45	-33.33	-31.64	-33.43	1.35
	Summer 2021	-34.83	-33.19	-31.55	-33.19	2.32	-32.25	-31.34	-30.43	-31.34	1.29
Fungus	Fall 2020	-22.71	-22.71	-22.71	-22.71	0.00	-23.05	-23.05	-23.05	-23.05	0.00
Grass	Fall 2020	-33.53	-31.98	-29.06	-31.83	1.31	-35.05	-32.68	-30.85	-32.78	1.37
	Summer 2021	-31.03	-30.88	-30.73	-30.88	0.21	-35.05	-35.05	-35.05	-35.05	0.00
Rush	Fall 2020	-30.84	-30.84	-30.84	-30.84	0.00	-	-	-	-	-
Shrub	Fall 2020	-33.72	-31.79	-29.18	-31.94	1.64	-34.37	-33.36	-30.60	-32.83	1.49

Continued

Table 3.1 Continued

	Summer 2021	-31.97	-31.44	-30.91	-31.44	0.75	-32.96	-32.54	-32.12	-32.54	0.59
Fruits and Nuts	Fall 2020	-29.06	-28.20	-27.13	-28.04	0.63	-30.23	-27.27	-24.34	-26.99	2.05
	Summer 2021	-25.14	-25.14	-25.14	-25.14	0.00	-	-	-	-	-
Detritus	Summer 2019	-31.14	-28.75	-26.60	-28.74	1.07	-30.94	-28.82	-27.00	-28.82	0.91
	Winter 2020	-30.09	-29.04	-27.12	-29.01	0.74	-30.37	-29.35	-27.84	-29.22	0.63
	Summer 2020	-29.94	-28.29	-26.61	-28.36	0.90	-31.01	-28.55	-25.56	-28.33	1.12
	Winter 2021	-30.39	-28.37	-25.67	-28.46	0.89	-29.76	-28.67	-26.26	-28.51	0.95

Omnivorous small mammals (*Peromyscus spp.* and chipmunks) had similar δ^{13}C and δ^{15}N values (*Table 3.1, Table 3.2,* Appendix E). Due to the similarity of δ^{13}C and δ^{15}N among forbs, shrubs, grasses, we combined these three resources into a single resource (vegetation) for inclusion in our mixing model.

Table 3.2: Summary statistics for small mammal and basal resources δ^{15}N (per mill relative to air x 1000) at experimental sites by sampling period and reach, including minima (Min), medians, maxima (Max), mean, and standard deviation (SD).

		δ^{15}N (‰)									
		Lit Reaches					Unlit Reaches				
		Min	Median	Max	Mean	SD	Min	Median	Max	Mean	SD
Biotic Variable	Season										
Small Mammals											
Peromyscus spp.	Fall 2020	4.16	6.01	7.11	5.74	0.96	4.27	6.31	7.60	6.08	1.01
	Summer 2021	3.5	6.00	7.6	5.87	0.99	2.9	6.00	8.5	5.96	1.24
Blarina brevicauda	Fall 2020	4.18	4.18	4.18	4.18	0.00	-	-	-	-	-
	Summer 2021	5.6	5.6	5.6	5.6	0.00	-	-	-	-	-
Tamias striatus	Fall 2020	4.77	4.77	4.77	4.77	0.00	-	-	-	-	-
	Summer 2021	3.5	5.45	8.5	5.85	1.81	6.2	6.2	6.2	6.2	0.00
Didelphis virginiana	Summer 2021	7.50	7.65	7.80	7.65	0.15	-	-	-	-	-
Aquatic Basal Sources											
Periphyton	Summer 2020	-0.09	5.06	9.39	4.77	2.55	-1.14	5.17	9.63	5.36	2.34
	Winter 2021	-7.80	6.58	11.05	5.80	4.46	-9.06	6.78	10.67	5.80	4.29

Continued

Table 3.2 Continued

Terrestrial Basal Sources											
Forb	Fall 2020	-3.37	0.69	6.03	0.90	2.67	-3.39	-0.28	6.21	0.32	2.80
	Summer 2021	0.00	1.92	3.83	1.92	2.71	-0.25	-0.07	0.12	-0.07	0.26
Fungus	Fall 2020	3.19	3.19	3.19	3.19	0.00	5.81	5.81	5.81	5.81	0.00
Grass	Fall 2020	-1.90	1.05	6.59	1.51	2.40	-3.85	0.58	9.72	1.30	3.87
	Summer 2021	0.14	2.39	4.64	2.39	3.18	-2.78	-2.78	-2.78	-2.78	0.00
Rush	Fall 2020	5.98	5.98	5.98	5.98	0.00	-	-	-	-	-
Shrub	Fall 2020	-4.00	-0.08	1.08	-0.50	1.38	-3.69	-0.18	2.06	-0.50	2.04
	Summer 2021	-3.34	-1.15	1.04	-1.15	3.10	-3.91	-0.83	2.26	-0.83	4.36
Fruits and Nuts	Fall 2020	-2.28	0.20	4.19	0.49	1.99	-1.23	0.00	3.83	0.70	1.99
	Summer 2021	0.41	0.41	0.41	0.41	0.00	-	-	-	-	-
Detritus	Summer 2019	-1.51	2.21	5.85	2.13	1.78	-0.73	2.72	6.85	2.60	1.88
	Winter 2020	-0.91	1.63	5.53	2.01	1.46	-2.69	2.06	5.37	2.03	1.68
	Summer 2020	-0.34	2.15	6.50	2.25	1.51	-0.99	2.61	5.36	2.56	1.73
	Winter 2021	-1.31	2.76	6.46	2.72	1.89	-0.10	2.47	5.81	2.21	1.33

Diet Proportions and Trophic Position of Peromyscus

The *Peromyscus* hair samples had $\delta^{13}C$ and $\delta^{15}N$ isotopic compositions most consistent with fruits and nuts (*Figure 3.2*). The hair samples had similar $\delta^{15}N$ isotopic compositions to terrestrial vegetation, but different $\delta^{13}C$ compositions. While the hair samples had similar $\delta^{13}C$ compositions to periphyton, they were less enriched in ^{15}N than the periphyton samples. Plots of the chipmunks, shrews, and opossums show similar positions in isospace (Appendix F).

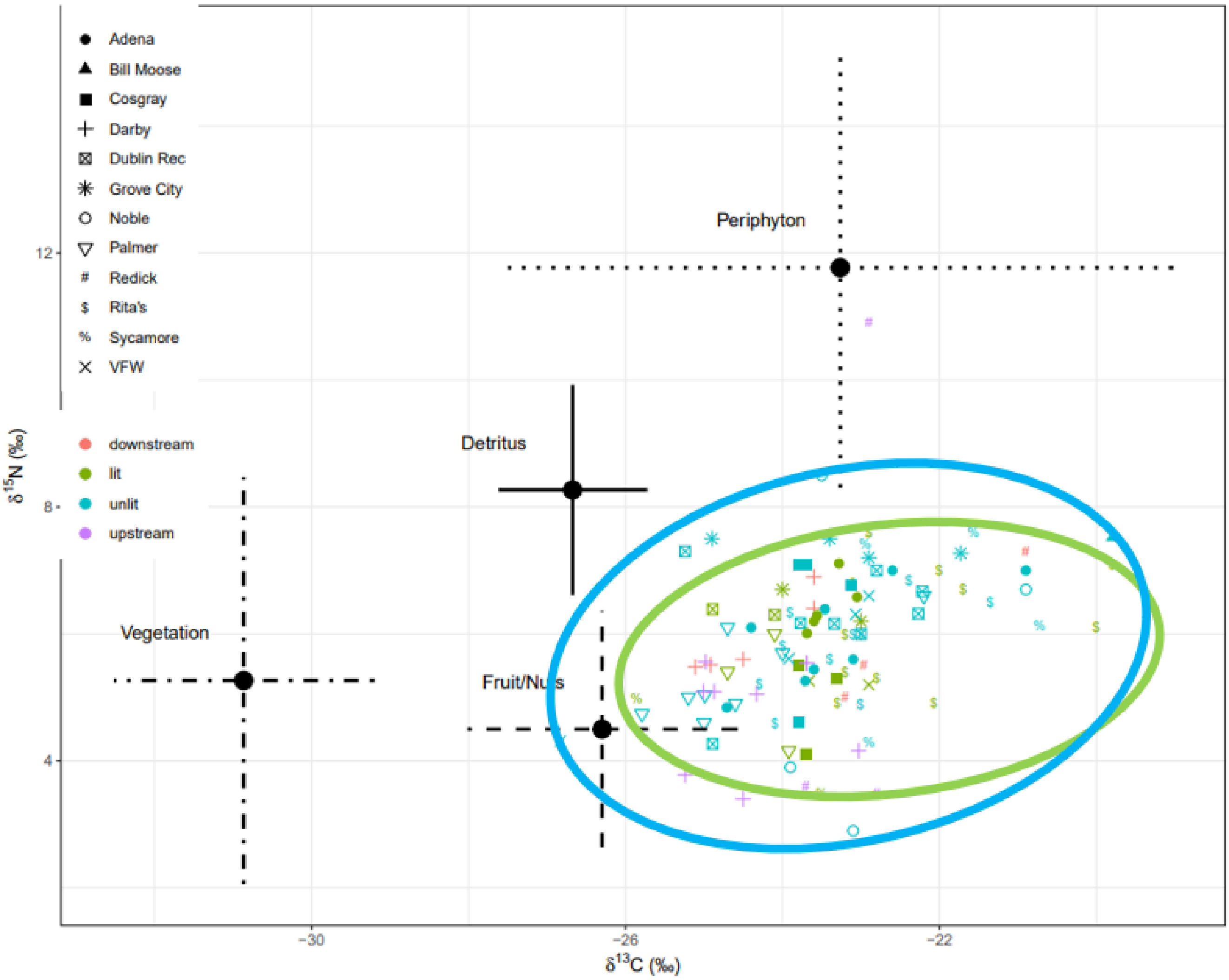


Figure 3.2: Isospace plot of δ^{13}C (‰) and δ^{15}N (‰) values for *Peromyscus* hair and basal resource samples. Basal resource bars show range of values for samples. Points= symbols represent sites while point colors represent reaches where hair samples were collected; Ovals= spread of lit (green) and unlit (blue) isotopic compositions.

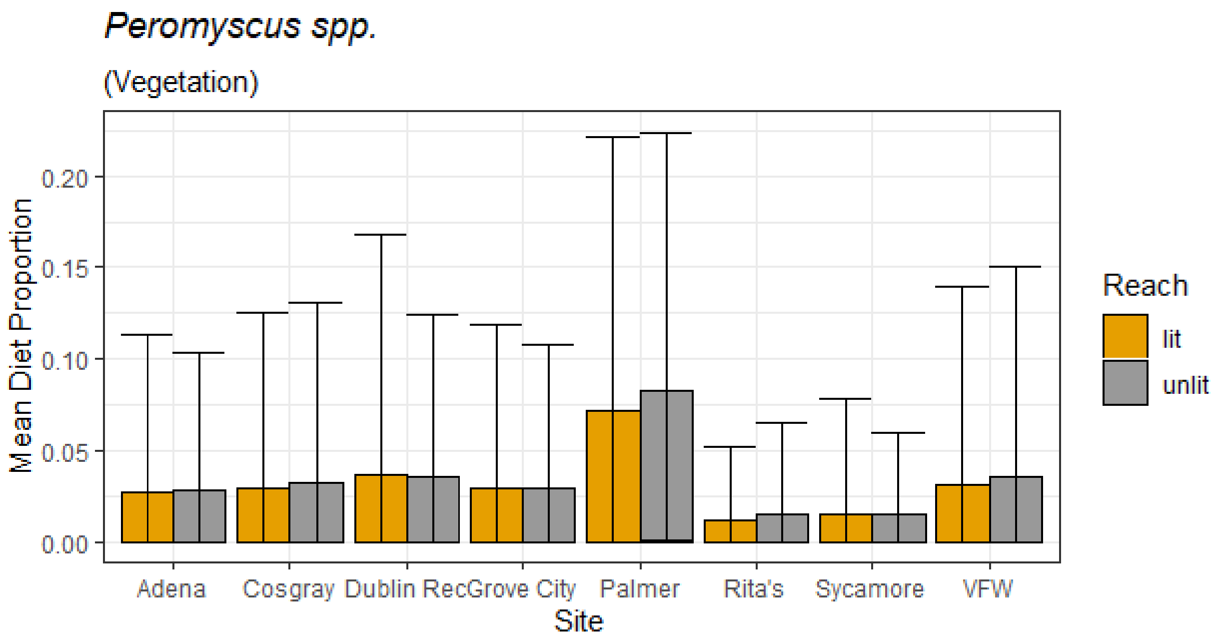
For all paired comparisons, we omitted two of the sites (Bill Moose and Noble) due to *Peromyscus* only being captured at one reach instead of both. The mean and standard deviation results of the MCMC *Peromyscus* mixing model, as well the trophic positions calculated from the diet proportions, show differences between lit and unlit reaches in the individual diet proportions of different basal resources but not in the average trophic position (*Table 3.3*). Detritus, fruits and nuts, and the total terrestrial diet had higher mean diet proportions at lit sites compared to unlit sites, while vegetation and periphyton diet proportions had the opposite trend. The results of the paired *t*-test in the table show significant differences ($p<0.05$) in detritus diet composition, total terrestrial diet composition, and periphyton/total aquatic diet composition and trends ($p<0.1$) in fruits and nuts diet composition and vegetation diet composition between lit and unlit reaches.

The average trophic position at lit reaches was 2.135 and the trophic position at unlit reaches was 2.166 ($t = -1.334$, $df = 7$, $p = 0.224$).

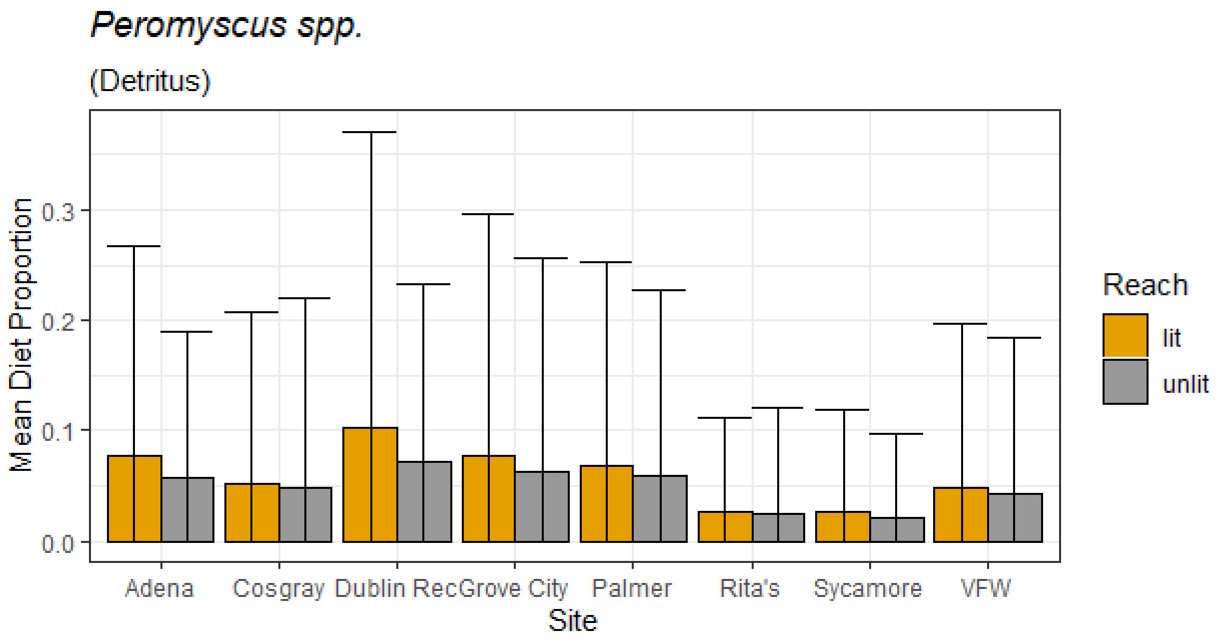
Table 3.3: Mean and standard deviation of trophic position and estimated diet proportions of basal resources from terrestrial and aquatic sources, separated by lit vs unlit reaches for *Peromyscus*. Paired t-tests compare the means of lit vs unlit reaches, with significant p-values (α=0.05) denoted with a * and trends (α=0.1) denoted with a ^.

	Lit Reach		Unlit Reach		Paired T-test Results		
Variable	Mean	SD	Mean	SD	*t*	*df*	*p*
Trophic Position	2.135	0.278	2.166	0.321	-1.334	7	0.224
Terrestrial Basal Resources							
Detritus Diet Proportion	0.060	0.027	0.048	0.018	3.147	7	0.016*
Fruits and Nuts Diet Proportion	0.855	0.059	0.843	0.061	2.321	7	0.053^
Vegetation Diet Proportion	0.031	0.018	0.034	0.021	-2.081	7	0.076^
Total Terrestrial Diet Proportion	0.951	0.023	0.933	0.035	4.391	7	0.003*
Aquatic Basal Resources							
Periphyton/Total Aquatic Diet Proportion	0.048	0.023	0.067	0.034	-4.637	7	0.002*

Most of the experimental sites had similar mean diet proportions for the four different basal resources at lit and unlit reaches for the same site (*Figure 3.3*). For the four different basal resources, there were consistent trends across all sites. However, none of the individual sites were different for any of the basal resource contributions based on credible intervals.


Peromyscus spp.

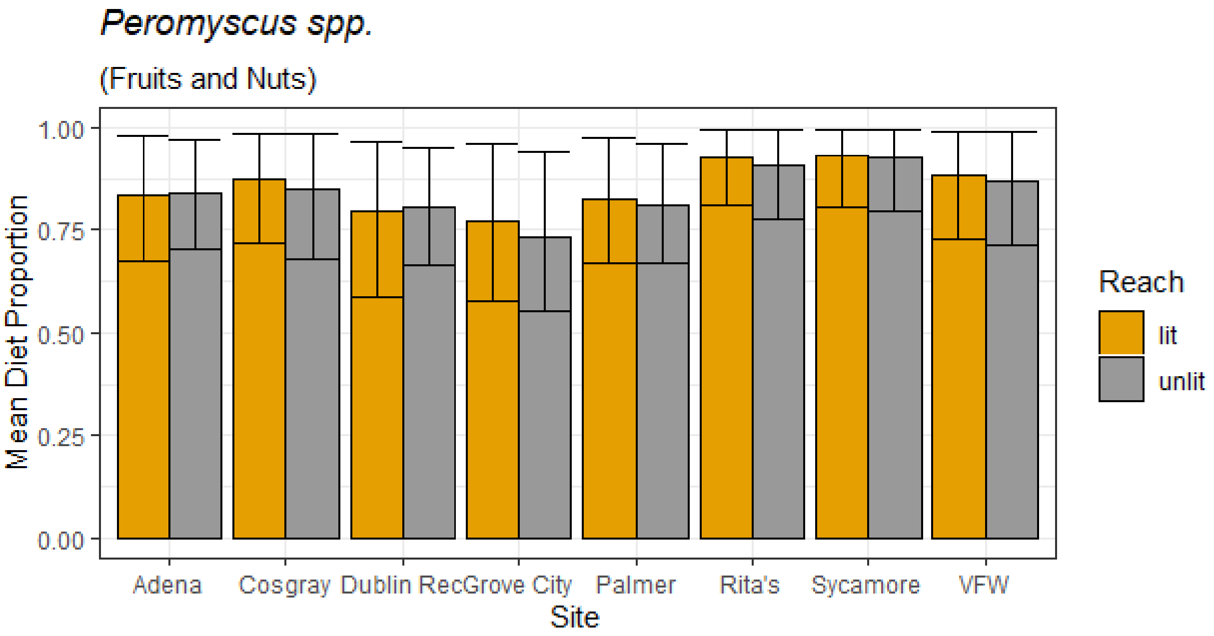
(Vegetation)


Peromyscus spp.

(Detritus)

Continued

Figure 3.3 Continued



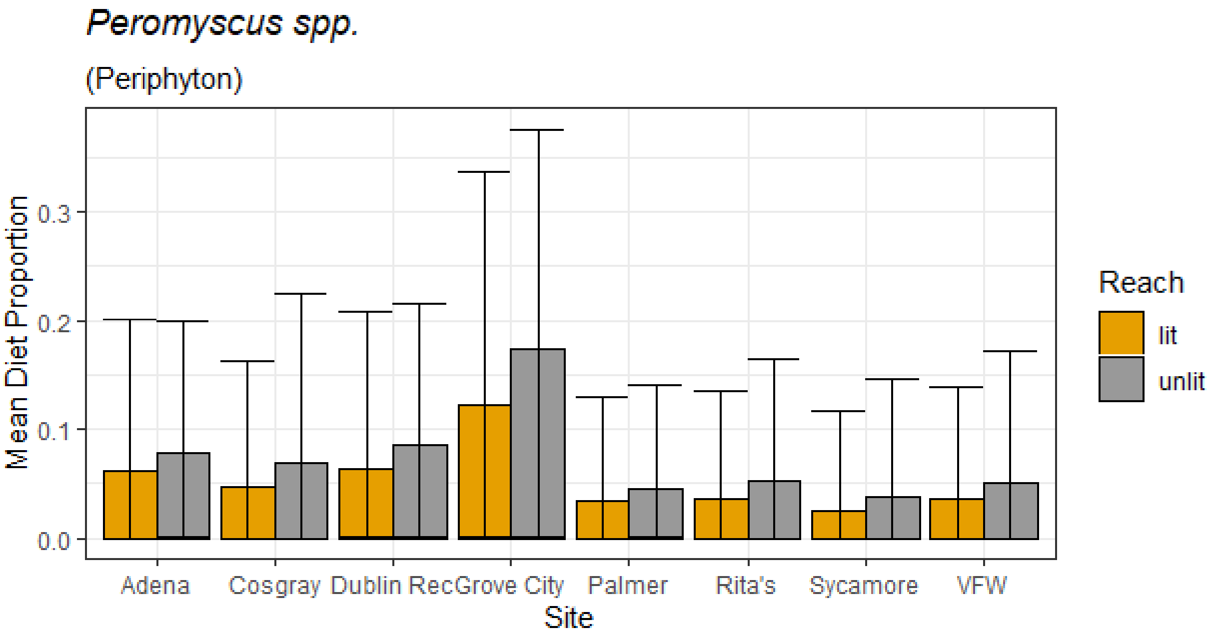
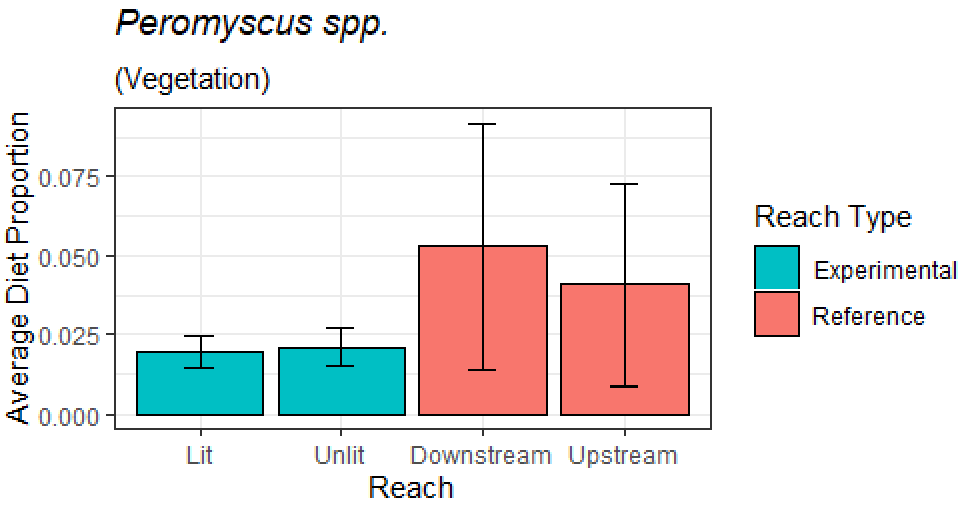


Figure 3.3: Estimated median diet proportions of basal carbon sources for: vegetation (first), detritus (second), fruits and nuts (third), and periphyton (fourth) for *Peromyscus* in experimental sites. Estimated proportions separated by reach type with credible intervals.

Standard error bars overlapped between experimental and reference sites for vegetation, detritus, and fruits/nuts diet contributions, indicating no significant difference between experimental and control sites (*Figure 3.4*). Periphyton diet contributions did not have overlapping error bars between experimental reaches and the upstream reference reaches, but there is also a large difference between the upstream and downstream reference reaches.



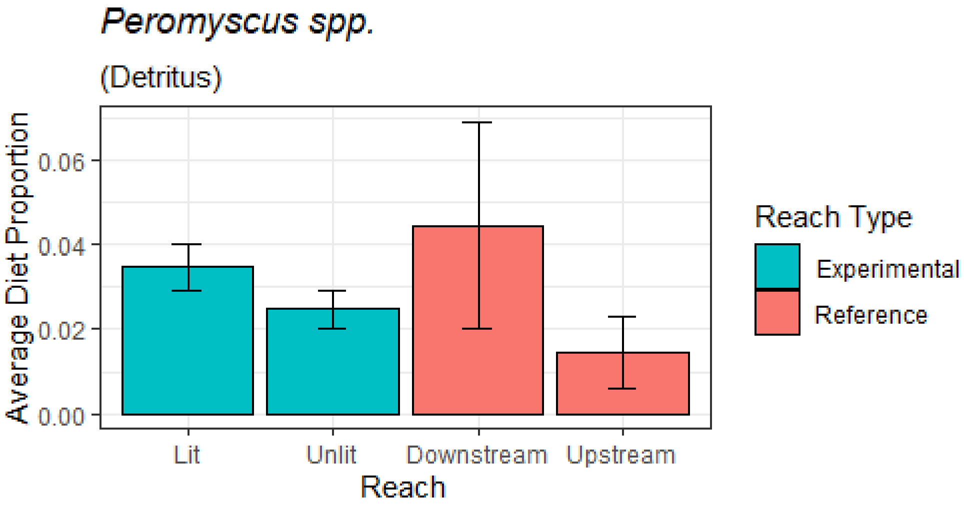


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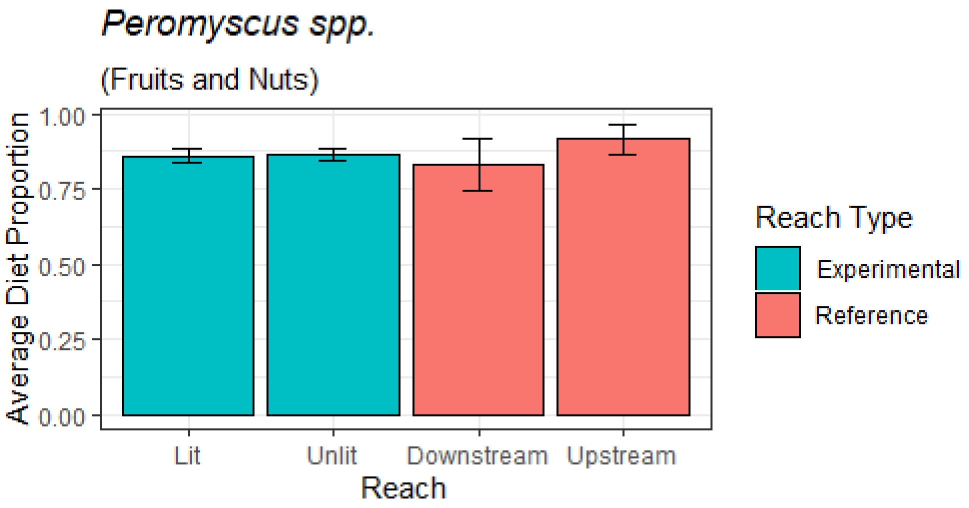
Figure 3.4 Continued



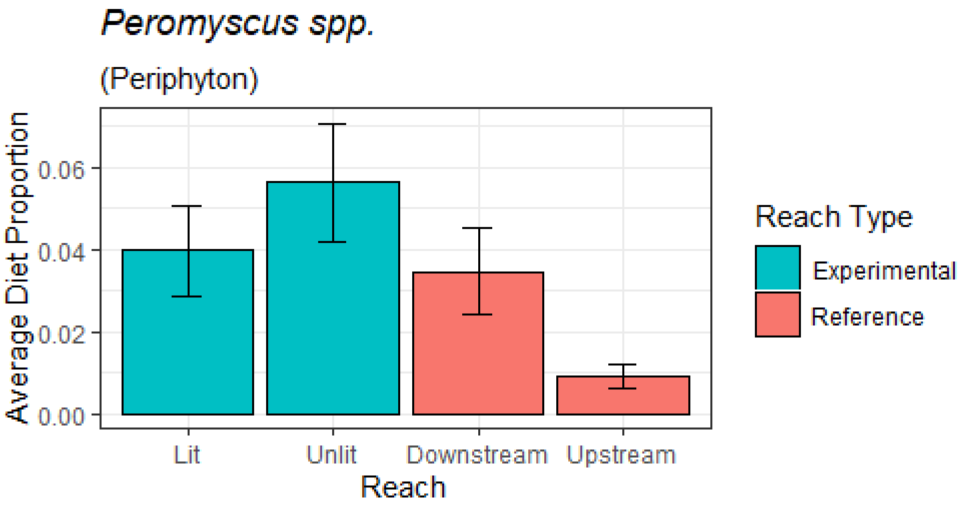


Figure 3.4: Averages of estimated mean diet proportions of basal carbon sources for: vegetation (first), detritus (second), fruits and nuts (third), and periphyton (fourth) for *Peromyscus* between all reach types. Error bars are standard error.

There was no difference in trophic position between lit and unlit reaches (*Figure 3.5*). One outlier was identified at an unlit reach (TP = 2.63). Trophic position had a greater interquartile range at lit reaches compared to unlit reaches, but both reach types had similar overall ranges due to the outlier.

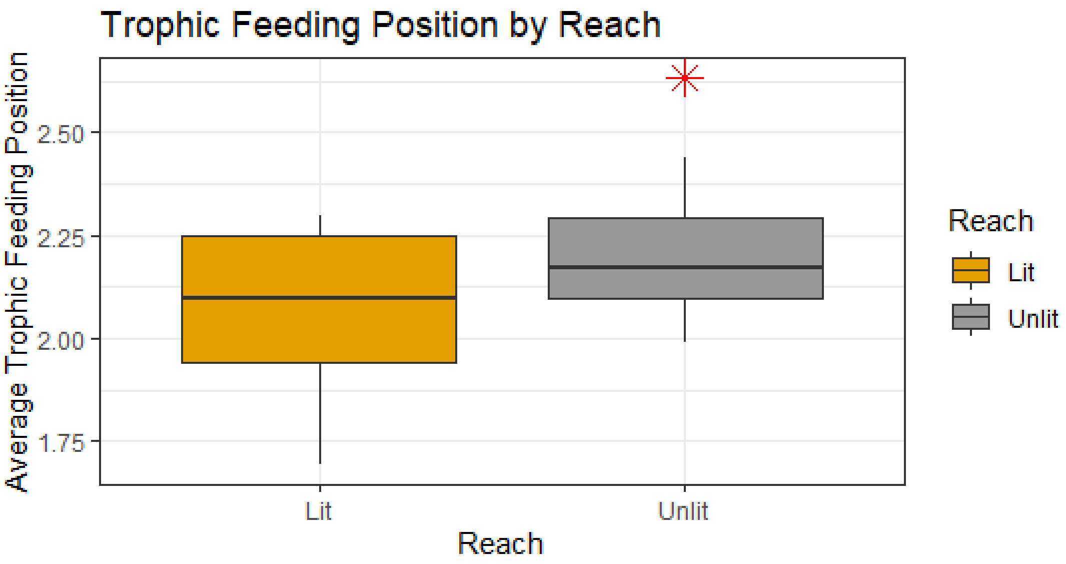


Figure 3.5: Boxplot of average feeding position for *Peromyscus* by reach with outliers marked with red star and middle lines across boxes representing the median feeding position for reach type.

Linear Mixed-Effect Models

We used the first set of LMMs with reach instead of lux to understand the impact of ALAN presence/absence on trophic position/basal resource energy contributions. Trophic position, the proportion of energy derived from fruits and nuts, and the proportion of energy derived from terrestrial vegetation were not associated with any explanatory variables, including ALAN presence (reach) (*Table 3.4*). The proportion of energy derived from detritus was negatively associated with unlit reaches ($R^2 = 0.952$, $F = 14.393$, $p = 0.013$) and there was a trend in a negative association with canopy cover ($R^2 = 0.952$, $F = 3.661$, $p = 0.092$). The proportion of energy derived from periphyton was positively associated with unlit reaches ($R^2 = 0.898$, $F = 9.380$, $p = 0.022$). The random variable – site – explained most of the variation in all diet proportion models.

Table 3.4: Linear mixed-effect model results for feeding position and separate basal resources in *Peromyscus*. F-statistics from ANOVAs show significance of each explanatory variable on the response, with significant p-values (α=0.05) denoted with a * and trends (α=0.1) denoted with a ^. The difference between the Conditional R^2 (Con. R^2) and Marginal R^2 (Mar. R^2) is the amount of model variation explained by the random effect variable (site).

Explanatory Variable	Estimate	SE	*df*	*F*-statistic	*p*	Con. R^2	Mar. R^2
Trophic Position						NA	0.328
Impervious Surface	0.042	0.054	13	0.604	0.451		
Sediment Size	-0.079	0.047	13	2.866	0.114		
Reach	0.093	0.109	13	0.724	0.410		
Canopy Cover	-0.054	0.052	13	1.112	0.311		
Detritus Diet Proportion						0.952	0.145
Impervious Surface	0.001	0.005	12.209	0.07	0.784		
Sediment Size	0.000	0.002	4.480	0.009	0.928		
Reach	-0.016	0.004	4.914	14.393	0.013*		
Canopy Cover	-0.009	0.005	7.995	3.661	0.092^		
Fruits and Nuts Diet Proportion						0.960	0.057
Impervious Surface	0.008	0.011	11.198	0.565	0.468		
Sediment Size	-0.002	0.005	4.477	0.104	0.762		
Reach	-0.011	0.008	4.915	1.688	0.252		
Canopy Cover	0.010	0.010	7.271	0.994	0.351		
Periphyton Diet Proportion						0.898	0.185
Impervious Surface	-0.011	0.007	12.828	2.119	0.169		
Sediment Size	-0.002	0.004	5.963	0.118	0.743		
Reach	0.022	0.007	6.009	9.380	0.022*		
Canopy Cover	-0.006	0.008	11.729	0.552	0.472		
Vegetation Diet Proportion						0.976	0.012
Impervious Surface	-0.002	0.003	9.193	0.263	0.620		
Sediment Size	0.001	0.001	4.714	1.038	0.358		
Reach	0.003	0.002	5.093	2.597	0.167		
Canopy Cover	0.000	0.003	6.527	0.007	0.935		

The second set of LMMs analyzed impacts of light intensity on trophic position/basal resource diet proportions by removing unlit reaches to reduce zero inflation. Trophic position was not associated with light intensity ($R^2 = 0.308$, $F = 2.666$, $p = 0.154$), and neither were any of the basal diet proportions (Detritus: $R^2 = 0.911$, $F = 0.783$, $p = 0.41$; Fruits and Nuts: $R^2 =$

0.087, $F = 0.568$, $p = 0.479$; Periphyton: $R^2 = 0.021$, $F = 0.345$, $p = 0.565$; Vegetation: $R^2 = 0.169$, $F = 1.218$, $p = 0.312$).

Discussion

In riparian areas of small streams in Columbus, Ohio, we found evidence to support that ALAN impacted trophic interactions of *Peromyscus* and their energy pathways. Reach type, which represents the presence or absence of ALAN, appeared to have the largest impact on changes to the diet contribution of different basal resources. This is a similar finding to responses by terrestrial arthropod consumers in Columbus, Ohio that consumed different diet contributions under ALAN (Sullivan et al. 2019). Feeding position was not influenced by the presence or absence of ALAN, but it did decrease under greater light intensity. A possible explanation for this is higher lux values are associated with decreases in body size and diversity of aquatic invertebrates emerging from streams (Meyer and Sullivan 2013), causing *Peromyscus* to switch to more available food sources in the form of terrestrial basal resources. This is supported by a higher diet proportion of fruits and nuts that *Peromyscus* are consuming under greater light intensities.

There also appears to be a trend in canopy cover decreasing the proportion of energy derived from detritus by *Peromyscus*. This is the opposite trend of what would be expected since small streams are often dependent on allochthonous contributions of energy (Hynes 1975, Vannote et al. 1980). A possible explanation is that some streams in our study system are closely linked to larger stream systems. Invertebrate communities in larger streams typically consist of more filter feeders that are unable to take advantage of larger stream detritus (Vannote et al. 1980). Due to proximity of these small urban streams to larger systems, the invertebrate communities could be like larger systems, meaning increases in canopy cover and detrital inputs would not increase the abundances of invertebrates emerging from the streams that *Peromyscus* would be able to consume.

We hypothesized that small mammals would consume a lower diet proportion of aquatic basal resources at reaches where ALAN was present. This hypothesis was supported by *Peromyscus* consuming a lower proportion of aquatically-derived energy at lit reaches. This could be explained by the “vacuum cleaner” effect (reduction in abundances of emergent macroinvertebrates from greater predation and reduced oviposition) and the decreases to body size, abundance, and community composition of emergent aquatic insects under ALAN (Rydell 1992, Meyer and Sullivan 2013). Another explanation is ALAN changing *Peromyscus* foraging behavior. Small mammals avoid foraging patches and change foraging time under ALAN (Bird et al. 2004, Shier et al. 2020). Lack of vegetation cover and greater predation risk near streams could be reducing *Peromyscus* foraging on emergent macroinvertebrates along stream edges. However, there was an increase of aquatic detritus in *Peromyscus* diets at lit reaches. While aquatic detritus in these systems come mainly from allochthonous sources (Vannote et al. 1980), the only way for *Peromyscus* to be taking in energy from that pathway is through emergent invertebrates. A reduction in macroinvertebrate emergence would not explain the increase in energy derived from aquatic detritus. Since aquatic invertebrate communities can shift under ALAN to a higher proportion of detritivores (Sullivan et al. 2019), the changes in aquatic basal resource consumption may be explained by a shift in community composition rather than a change in emergent invertebrate abundance or body size.

We also hypothesized that feeding position of small mammals would be lower when ALAN was present, but that hypothesis was not supported. A possible explanation is that instead of consuming a reduced proportion of invertebrates, *Peromyscus* are consuming different invertebrates due to changes in invertebrate community composition in the presence of ALAN (Sullivan et al. 2019). Switching to different invertebrates rather than to terrestrial basal resources would not change their feeding position.

We did not observe any patterns across light intensities. I hypothesized that increases in ALAN light intensity would strengthen the negative relationship between ALAN and aquatic basal resource subsidies/feeding position of small mammals. This was not supported by the data. Lack of differences could be caused by the low light intensities we observed, where moderate and high levels of ALAN are needed to change macroinvertebrate communities (Sullivan et al. 2019). Higher light intensities can lead to smaller body sizes of emergent insects (Meyer and Sullivan 2013) and a lower total abundance of emergent insects due to higher predation rates of larger bodied macroinvertebrates attracted to light sources (Horvath et al. 2009). However, our light intensities may not have been great enough to observe these differences. While the light intensities we observed (0.28-3.0 lux) were greater than typical nighttime lighting with no

ALAN present (full moon = 0.1 lux), they were up to 50x lower than other ALAN studies (Bliss-Ketchum et al. 2016).

Potential Drivers

A potential driver for the changes in basal resource diet contributions and feeding position is changes to aquatic and terrestrial macroinvertebrate communities under ALAN, as identified by Sullivan et al. (2019). We can address possible differences in macroinvertebrate communities in these systems with research to identify collected aquatic macroinvertebrate samples. These possible macroinvertebrate community changes could be driven by predator-prey interactions that change under ALAN (reviewed in Perkin et al. 2011). Within the stream, aquatic macroinvertebrates can be under greater predation pressure from insectivorous fish under ALAN due to greater visibility at night improving predation success (Moore et al. 2006, Nightingale et al. 2006). Thus, ALAN may be reducing population sizes of aquatic invertebrates through predation, which in turn reduces the abundance of aquatic invertebrates that can emerge from the stream as adults and be taken up by small mammals living along the stream. Since *Peromyscus* consume most food sources, a reduction in high densities of emergent invertebrates could result in prey-switching to more terrestrial invertebrates or vegetation sources.

Another potential driver is changes to invertebrate communities caused by positive phototaxis of some invertebrates to artificial lighting sources. Aquatic invertebrates use light cues to indicate timing for reproduction, self-orientation, and to locate and colonize aquatic systems (Horvath et al. 2011, Horvath and Csabai 2014), so ALAN presence can alter those cues. Attraction to lighting sources by emergent invertebrates can also influence communities by impacting dispersal and increasing mortality both directly and through increased predation (Eisenbeis 2006, Horvath et al. 2009). Terrestrial invertebrates can also exhibit positive phototaxis, with reflections of light off the water surface attracting terrestrial insects to the water and disorienting them (Schwind 1991). All these positive phototaxis responses in invertebrates could impact community composition and abundances, changing what *Peromyscus* consume at lit reaches compared to unlit reaches.

A final potential driver for changes to diet proportions of basal resources and feeding position under ALAN is changes to foraging behavior of small mammals. Even though we did not observe a difference in small mammal captures in Chapter 2, small mammals can show avoidance behavior from ALAN to avoid predation (Shier et al. 2020). This impacts small mammal foraging, where small mammals exhibit less frequent and less prolonged foraging behavior when ALAN is present (Bird et al. 2004). This disturbance in foraging behavior by ALAN could alter the types of invertebrates and basal resources that small mammals are consuming under ALAN, changing their consumed diet proportions and feeding position.

Conclusions

Artificial light at night is an ecological stressor that will continue to expand as urbanization expands. With over 90% of the United States and United Kingdom already exposed to elevated nighttime light levels (Cinzano et al. 2001) and nearly a quarter of continental land surfaces (excluding Antarctica) being exposed to ALAN (Falchi et al. 2016), more studies to understand the impact of ALAN on ecological processes need to be conducted. Most studies have focused on impacts at the individual and population level (Bishop 1969, Russart et al. 2018, Sanders and Gaston 2018), but more needs to be done to understand community-level impacts such as trophic interactions. This study provided insight into how trophic interactions and aquatic-terrestrial energy subsidies are impacted by ALAN in small urban streams. I found small changes in the diet proportions of different basal resources taken up by small mammals and the feeding position of small mammals at lit reaches compared to unlit reaches. These results are important to consider since they could indicate changes to aquatic invertebrate communities, which provide energy to both aquatic and terrestrial systems (Kato et al. 2003, Kautza and Sullivan 2016). They could also indicate changes in feeding behavior and possible fitness of small mammals, which are important sources of energy for terrestrial predators such as raptors, foxes, and coyotes (Lockie 1959, Kay et al. 1994, Gehrt and Riley 2010). The results from this study can be used to establish lighting thresholds to reduce the impact that ALAN has on riparian areas. However, these results need to be considered with the fact that the shifts in diet proportions and feeding position were relatively small. Additionally, the diet proportions were derived using Bayesian mixing models and then analyzed in a Frequentist framework, which does not incorporate error from the mixing models and likely overestimates statistical power. Using an alternative method of comparing credible intervals of estimated diet proportions showed no differences between lit and unlit reaches (Appendix G), indicating that our results may be overestimating differences due to lack of error incorporation. We hope to finish identification of aquatic macroinvertebrates and receive the results of the isotope analysis of emergent aquatic macroinvertebrates in these systems to incorporate into the model to understand more completely what is causing these differences. Where possible, future studies should complete a similar study at streams with greater light intensity to discern if more intense lux values than what we observed would show a greater difference between lit and unlit reaches.

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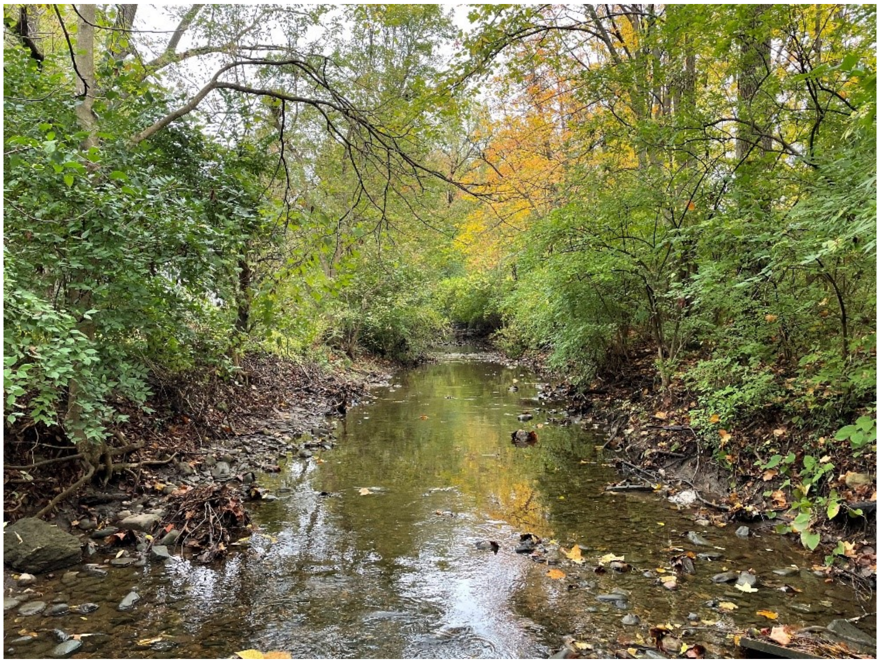
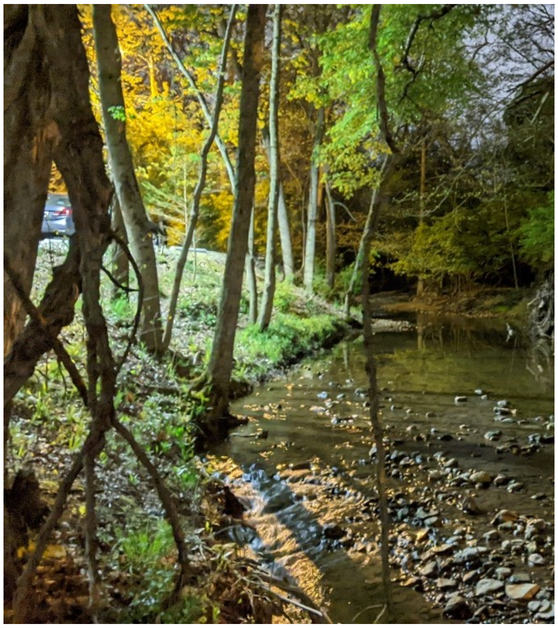
Appendix A*:* Site pictures of canopied small streams in Columbus, Ohio (first: Rita's daytime lit reach; second: VFW daytime lit reach; third: Sycamore nighttime lit reach; fourth: Bill Moose nighttime lit reach).





Appendix B: White-footed mouse (*Peromyscus leucopus*) population estimates using both the Cormack-Jolly-Seber model and Pollock's Robust Model based on mark-recapture data, including the number of individuals that survived/did not emigrate from the population between trapping periods (Survival), the abundance estimates for that trapping period (N per TP), the number of individuals that were born/immigrated into the population between trapping periods (Birth), and the total abundance estimate (Total N).

		CJS Model		Robust Model	
		Estimate	SE	Estimate	SE
Variable	Trapping Period				
Adena Lit					
Survival	Autumn 2020 -> Summer 2021	0.4834	6.186×10^{4}	1.938×10^{-9}	2.669×10^{-5}
	Summer 2021 -> Autumn 2021	-	-	1.000	0
N per TP	Autumn 2020	-	-	1.032×10^{9}	1.422×10^{13}
	Summer 2021	8.377×10^{9}	1.172×10^{15}	2.000	1.751×10^{-1}
	Autumn 2021	-	-	1.032×10^{9}	1.422×10^{13}
Birth	Autumn 2020 -> Summer 2021	-	-	0	0
	Summer 2021 -> Autumn 2021	-	-	1.032×10^{9}	1.422×10^{13}
Total N	All Seasons	8.377×10^{9}	1.172×10^{15}	2.064×10^{9}	2.011×10^{13}
Adena Unlit					
Survival	Autumn 2020 -> Summer 2021	0.2417	3.093×10^{4}	3.661×10^{-9}	2.595×10^{-5}
	Summer 2021 -> Autumn 2021	-	-	3.671×10^{-9}	2.599×10^{-5}
N per TP	Autumn 2020	-	-	2.000	1.751×10^{-1}
	Summer 2021	8.377×10^{9}	1.172×10^{15}	2.000	1.751×10^{-1}
	Autumn 2021	-	-	3.000	4.380×10^{-2}
Birth	Autumn 2020 -> Summer 2021	-	-	2.000	1.425
	Summer 2021 -> Autumn 2021	-	-	3.000	1.732
Total N	All Seasons	8.377×10^{9}	1.172×10^{15}	7.000	2.515×10^{-1}
Bill Moose Lit					
Survival		-	-	-	-
		-	-	-	-
N per TP		-	-	-	-

	No Captures	-	-	-	-
		-	-	-	-
Birth		-	-	-	-
		-	-	-	-
Total N		-	-	-	-
Bill Moose Unlit					
Survival	Autumn 2020 -> Summer 2021	1.116×10^{-10}	8.475×10^{-6}	1.614×10^{-9}	2.829×10^{-5}
	Summer 2021 -> Autumn 2021	-	-	1.000	0
N per TP	Autumn 2020	-	-	2.453	3.292×10^{4}
	Summer 2021	2.232×10^{-10}	8.011×10^{-6}	3.960×10^{-9}	0
	Autumn 2021	-	-	2.453	3.292×10^{4}
Birth	Autumn 2020 -> Summer 2021	-	-	0	0
	Summer 2021 -> Autumn 2021	-	-	2.453	3.292×10^{4}
Total N	All Seasons	2.000	0	4.907	4.577×10^{4}
Cosgray Lit					
Survival	Autumn 2020 -> Summer 2021	1.000	0	1.000	0
	Summer 2021 -> Autumn 2021	-	-	3.363×10^{-2}	1.722×10^{3}
N per TP	Autumn 2020	-	-	1.709×10^{-9}	0
	Summer 2021	6.000	4.299×10^{5}	4.583×10^{16}	6.050×10^{20}
	Autumn 2021	-	-	1.541×10^{15}	7.627×10^{19}
Birth	Autumn 2020 -> Summer 2021	-	-	4.583×10^{16}	6.050×10^{20}
	Summer 2021 -> Autumn 2021	-	-	0	0
Total N	All Seasons	12.000	4.299×10^{5}	4.583×10^{16}	6.050×10^{20}
Cosgray Unlit					
Survival	Autumn 2020 -> Summer 2021	6.465×10^{-1}	8.186×10^{4}	1.000	0
	Summer 2021 -> Autumn 2021	-	-	7.551×10^{-10}	7.770×10^{-6}
N per TP	Autumn 2020	-	-	6.622×10^{9}	6.814×10^{13}
	Summer 2021	1.498×10^{10}	2.058×10^{13}	6.622×10^{9}	6.814×10^{13}
	Autumn 2021	-	-	5.000	6.824×10^{-1}
Birth	Autumn 2020 -> Summer 2021	-	-	0	0

	Summer 2021 -> Autumn 2021	-	-	0	0
Total N	All Seasons	1.498 x 10^{10}	2.058 x 10^{13}	6.622 x 10^{9}	6.814 x 10^{13}
Dublin Rec Lit					
Survival	Autumn 2020 -> Summer 2021	1.516 x 10^{-10}	6.468 x 10^{-6}	1.643 x 10^{-9}	2.199 x 10^{-5}
	Summer 2021 -> Autumn 2021	-	-	5.156 x 10^{-1}	3.693 x 10^{-1}
N per TP	Autumn 2020	-	-	2.000	4.291 x 10^{-4}
	Summer 2021	4.000	1.706 x 10^{5}	8.000	4.899
	Autumn 2021	-	-	4.125	5.929 x 10^{-1}
Birth	Autumn 2020 -> Summer 2021	-	-	8.000	5.657
	Summer 2021 -> Autumn 2021	-	-	0	0
Total N	All Seasons	7.000	1.414	10.000	4.899
Dublin Rec Unlit					
Survival	Autumn 2020 -> Summer 2021	4.822 x 10^{-2}	6.288 x 10^{3}	1.000	5.521 x 10^{13}
	Summer 2021 -> Autumn 2021	-	-	4.412 x 10^{-9}	4.724 x 10^{-5}
N per TP	Autumn 2020	-	-	-	-
	Summer 2021	3.001 x 10^{9}	4.330 x 10^{14}	-	-
	Autumn 2021	-	-	-	-
Birth	Autumn 2020 -> Summer 2021	-	-	-	-
	Summer 2021 -> Autumn 2021	-	-	-	-
Total N	All Seasons	3.001 x 10^{9}	4.330 x 10^{14}	-	-
Grove City Lit					
Survival	Autumn 2020 -> Summer 2021	1.000	0	1.000	0
	Summer 2021 -> Autumn 2021	-	-	1.571 x 10^{-9}	1.700 x 10^{-5}
N per TP	Autumn 2020	-	-	3.512 x 10^{-9}	0
	Summer 2021	4.000	2.970 x 10^{5}	4.852	6.340 x 10^{4}
	Autumn 2021	-	-	2.000	1.751 x 10^{-1}
Birth	Autumn 2020 -> Summer 2021	-	-	4.852	6.340 x 10^{4}
	Summer 2021 -> Autumn 2021	-	-	2.000	1.425
Total N	All Seasons	6.000	2.970 x 10^{5}	6.852	6.340 x 10^{4}

Grove City Unlit

Survival	Autumn 2020 -> Summer 2021	6.465×10^{-1}	1.349×10^{5}	2.027×10^{-9}	6.083×10^{-5}
	Summer 2021 -> Autumn 2021	-	-	1.835×10^{-10}	5.454×10^{-6}
N per TP	Autumn 2020	-	-	3.646×10^{9}	7.709×10^{13}
	Summer 2021	4.073×10^{10}	9.226×10^{15}	7.390	1.574×10^{5}
	Autumn 2021	-	-	1.356×10^{-9}	0
Birth	Autumn 2020 -> Summer 2021	-	-	0	0
	Summer 2021 -> Autumn 2021	-	-	0	0
Total N	All Seasons	4.073×10^{10}	9.226×10^{15}	3.646×10^{9}	7.709×10^{13}

Noble Lit

Survival		-	-	-	-
		-	-	-	-
N per TP		-	-	-	-
	No Captures	-	-	-	-
		-	-	-	-
Birth		-	-	-	-
		-	-	-	-
Total N		-	-	-	-

Noble Unlit

Survival	Autumn 2020 -> Summer 2021	1.000	0	9.907×10^{-1}	1.093×10^{3}
	Summer 2021 -> Autumn 2021	-	-	1.202×10^{-9}	1.214×10^{-5}
N per TP	Autumn 2020	-	-	3.244×10^{-9}	0
	Summer 2021	6.000	4.300×10^{5}	3.000	9.904×10^{-1}
	Autumn 2021	-	-	1.000	1.121
Birth	Autumn 2020 -> Summer 2021	-	-	3.000	1.995
	Summer 2021 -> Autumn 2021	-	-	1.000	1.502
Total N	All Seasons	7.000	4.300×10^{5}	4.000	1.496

Palmer Lit

Survival	Autumn 2020 -> Summer 2021	4.833×10^{-1}	6.186×10^{4}	1.000	1.572×10^{13}
	Summer 2021 -> Autumn 2021	-	-	1.000	4.173×10^{13}

N per TP	Autumn 2020	-	-	-	-
	Summer 2021	8.377×10^{9}	1.172×10^{15}	-	-
	Autumn 2021	-	-	-	-
Birth	Autumn 2020 -> Summer 2021	-	-	-	-
	Summer 2021 -> Autumn 2021	-	-	-	-
Total N	All Seasons	8.377×10^{9}	1.172×10^{15}	-	-
Palmer Unlit					
Survival	Autumn 2020 -> Summer 2021	2.822×10^{-10}	1.383×10^{-5}	2.016×10^{-10}	6.542×10^{-6}
	Summer 2021 -> Autumn 2021	-	-	1.000	0
N per TP	Autumn 2020	-	-	2.976×10^{10}	9.655×10^{14}
	Summer 2021	1.523×10^{1}	8.460×10^{5}	6.000	3.317
	Autumn 2021	-	-	5.000	6.824×10^{-1}
Birth	Autumn 2020 -> Summer 2021	-	-	0	0
	Summer 2021 -> Autumn 2021	-	-	4.000	7.416
Total N	All Seasons	1.414×10^{1}	5.076×10^{5}	2.976×10^{10}	9.655×10^{14}
Rita's Lit					
Survival	Autumn 2020 -> Summer 2021	3.995×10^{-10}	3.572×10^{-5}	7.750×10^{-9}	7.457×10^{-5}
	Summer 2021 -> Autumn 2021	-	-	9.091×10^{-2}	8.668×10^{-2}
N per TP	Autumn 2020	-	-	3.058×10^{9}	2.943×10^{13}
	Summer 2021	4.741×10^{1}	4.770×10^{6}	2.370×10^{1}	2.942×10^{1}
	Autumn 2021	-	-	5.000	0
Birth	Autumn 2020 -> Summer 2021	-	-	0	0
	Summer 2021 -> Autumn 2021	-	-	2.845	3.502
Total N	All Seasons	4.579×10^{1}	3.903×10^{6}	3.058×10^{9}	2.943×10^{13}
Rita's Unlit					
Survival	Autumn 2020 -> Summer 2021	1.292×10^{-10}	5.869×10^{-6}	2.248×10^{-9}	2.408×10^{-5}
	Summer 2021 -> Autumn 2021	-	-	1.000	0
N per TP	Autumn 2020	-	-	1.711×10^{9}	2.478×10^{13}

	Summer 2021	1.452 x 10^{1}	7.203 x 10^{5}	1.683 x 10^{1}	9.135
	Autumn 2021	-	-	1.683 x 10^{1}	9.135
Birth	Autumn 2020 -> Summer 2021	-	-	1.298 x 10^{1}	6.927 x 10^{4}
	Summer 2021 -> Autumn 2021	-	-	0	0
Total N	All Seasons	1.384 x 10^{1}	2.401 x 10^{5}	1.711 x 10^{9}	2.477 x 10^{13}
Sycamore Lit					
Survival	Autumn 2020 -> Summer 2021	2.893 x 10^{-1}	3.773 x 10^{4}	1.000	0
	Summer 2021 -> Autumn 2021	-	-	1.000	0
N per TP	Autumn 2020	-	-	1.498 x 10^{9}	3.517 x 10^{13}
	Summer 2021	3.001 x 10^{9}	4.330 x 10^{14}	1.498 x 10^{9}	3.517 x 10^{13}
	Autumn 2021	-	-	1.938 x 10^{9}	2.588 x 10^{13}
Birth	Autumn 2020 -> Summer 2021	-	-	0	0
	Summer 2021 -> Autumn 2021	-	-	4.400 x 10^{8}	4.366 x 10^{13}
Total N	All Seasons	3.001 x 10^{9}	4.330 x 10^{14}	1.938 x 10^{9}	2.588 x 10^{13}
Sycamore Unlit					
Survival	Autumn 2020 -> Summer 2021	1.447 x 10^{-1}	1.886 x 10^{4}	1.000	3.431 x 10^{13}
	Summer 2021 -> Autumn 2021	-	-	1.000	2.015 x 10^{13}
N per TP	Autumn 2020	-	-	-	-
	Summer 2021	3.001 x 10^{9}	4.330 x 10^{14}	-	-
	Autumn 2021	-	-	-	-
Birth	Autumn 2020 -> Summer 2021	-	-	-	-
	Summer 2021 -> Autumn 2021	-	-	-	-
Total N	All Seasons	3.001 x 10^{9}	4.330 x 10^{14}	-	-
VFW Lit					
Survival	Autumn 2020 -> Summer 2021	2.893 x 10^{-1}	3.772 x 10^{4}	1.000	0
	Summer 2021 -> Autumn 2021	-	-	1.000	0
N per TP	Autumn 2020	-	-	1.465 x 10^{9}	3.400 x 10^{13}
	Summer 2021	3.001 x 10^{9}	4.330 x 10^{14}	1.465 x 10^{9}	3.400 x 10^{13}
	Autumn 2021	-	-	4.241 x 10^{9}	5.923 x 10^{13}

Birth	Autumn 2020 -> Summer 2021	-	-	0	0
	Summer 2021 -> Autumn 2021	-	-	2.776 x 10^{9}	6.830 x 10^{13}
Total N	All Seasons	3.001 x 10^{9}	4.330 x 10^{14}	4.241 x 10^{9}	5.923 x 10^{13}
VFW Unlit					
Survival	Autumn 2020 -> Summer 2021	9.644 x 10^{-2}	1.258 x 10^{4}	7.021 x 10^{-1}	1.959 x 10^{4}
	Summer 2021 -> Autumn 2021	-	-	1.000	0
N per TP	Autumn 2020	-	-	4.579 x 10^{9}	6.265 x 10^{13}
	Summer 2021	3.001 x 10^{9}	4.330 x 10^{14}	3.215 x 10^{9}	7.817 x 10^{13}
	Autumn 2021	-	-	3.215 x 10^{9}	7.817 x 10^{13}
Birth	Autumn 2020 -> Summer 2021	-	-	0	0
	Summer 2021 -> Autumn 2021	-	-	0	0
Total N	All Seasons	3.001 x 10^{9}	4.330 x 10^{14}	4.579 x 10^{9}	6.265 x 10^{13}

Appendix C: Small mammal trapping captures and camera trap encounters by site, reach, and season for total encounters, total species observed (species richness), and the most common species recorded (number of events in parentheses). No captures/encounters marked with (-).

Observation Method	Site	Reach	Season	N	Species Richness	Most Common Species
Small Mammal Trapping						
	Adena	Lit	Autumn 2020	7	2	*Peromyscus leucopus* (4)
			Summer 2021	4	2	*Peromyscus leucopus* (3)
			Autumn 2021	1	1	*Peromyscus leucopus* (1)
		Unlit	Autumn 2020	5	1	*Peromyscus leucopus* (5)
			Summer 2021	5	2	*Peromyscus leucopus* (3)
			Autumn 2021	5	1	*Peromyscus leucopus* (5)
	Bill Moose	Lit	Autumn 2020	1	1	*Tamias striatus* (1)
			Summer 2021	1	1	*Tamias striatus* (1)
			Autumn 2021	-	-	-
		Unlit	Autumn 2020	1	1	*Peromyscus leucopus* (1)
			Summer 2021	-	-	-
			Autumn 2021	1	1	*Peromyscus leucopus* (1)
	Cosgray	Lit	Autumn 2020	-	-	-
			Summer 2021	7	2	*Peromyscus leucopus* (5)
			Autumn 2021	6	1	*Peromyscus leucopus* (6)
		Unlit	Autumn 2020	1	1	*Peromyscus leucopus* (1)
			Summer 2021	3	1	*Peromyscus leucopus* (3)
			Autumn 2021	8	2	*Peromyscus leucopus* (7)
	Dublin Rec	Lit	Autumn 2020	3	1	*Peromyscus leucopus* (3)
			Summer 2021	2	2	*Peromyscus leucopus* (1)/ *Tamias striatus (1)*
			Autumn 2021	8	1	*Peromyscus leucopus* (8)
		Unlit	Autumn 2020	8	1	*Peromyscus leucopus* (8)
			Summer 2021	4	2	*Peromyscus leucopus* (3)
			Autumn 2021	10	1	*Peromyscus leucopus* (10)
	Grove City	Lit	Autumn 2020	1	1	*Peromyscus leucopus* (1)
			Summer 2021	2	1	*Peromyscus leucopus* (2)
			Autumn 2021	3	1	*Peromyscus leucopus* (3)
		Unlit	Autumn 2020	1	1	*Peromyscus leucopus* (1)
			Summer 2021	3	1	*Peromyscus leucopus* (3)
			Autumn 2021	-	-	-
	Noble	Lit	Autumn 2020	-	-	-

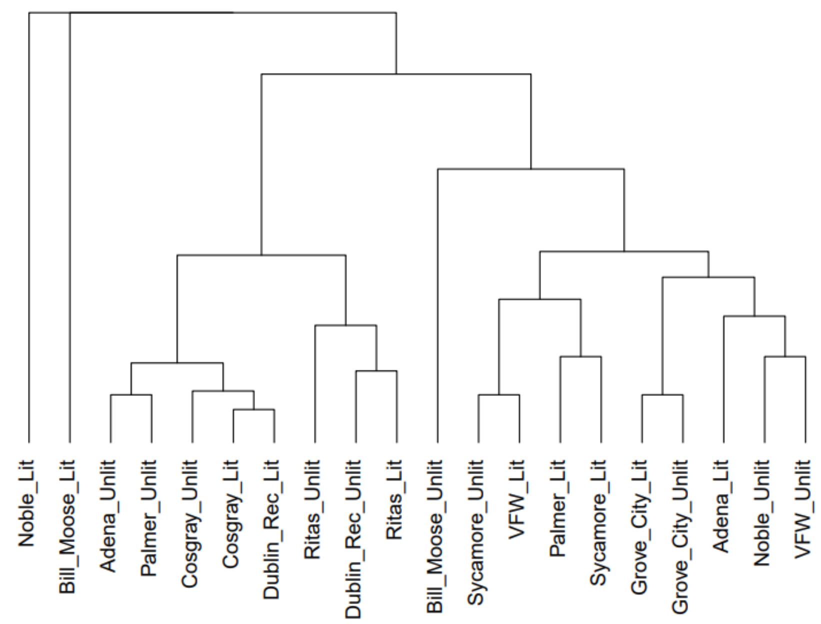
		Summer 2021	-	-	-
		Autumn 2021	-	-	-
	Unlit	Autumn 2020	-	-	-
		Summer 2021	5	1	*Peromyscus leucopus* (5)
		Autumn 2021	3	1	*Peromyscus leucopus* (3)
Palmer	Lit	Autumn 2020	3	3	*Blarina brevicauda* (1) / *Peromyscus leucopus* (1) / *Tamias striatus (1)*
		Summer 2021	4	2	*Didelphis virginiana* (2)/ *Peromyscus leucopus* (2)
		Autumn 2021	2	1	*Peromyscus leucopus* (2)
	Unlit	Autumn 2020	2	1	*Peromyscus leucopus* (2)
		Summer 2021	10	1	*Peromyscus leucopus* (10)
		Autumn 2021	2	1	*Peromyscus leucopus* (2)
Rita's	Lit	Autumn 2020	1	1	*Peromyscus leucopus* (1)
		Summer 2021	17	2	*Peromyscus leucopus* (16)
		Autumn 2021	8	2	*Peromyscus leucopus* (7)
	Unlit	Autumn 2020	5	1	*Peromyscus leucopus* (5)
		Summer 2021	8	1	*Peromyscus leucopus* (8)
		Autumn 2021	7	3	*Peromyscus leucopus* (4)
Sycamore	Lit	Autumn 2020	1	1	*Peromyscus leucopus* (1)
		Summer 2021	2	2	*Peromyscus leucopus* (1)/ *Tamias striatus (1)*
		Autumn 2021	3	2	*Peromyscus leucopus* (2)
	Unlit	Autumn 2020	3	1	*Peromyscus leucopus* (3)
		Summer 2021	1	1	*Peromyscus leucopus* (1)
		Autumn 2021	6	2	*Peromyscus leucopus* (4)
VFW	Lit	Autumn 2020	1	1	*Peromyscus leucopus* (1)
		Summer 2021	2	2	*Peromyscus leucopus* (1)/ *Tamias striatus (1)*
		Autumn 2021	6	2	*Peromyscus leucopus* (4)
	Unlit	Autumn 2020	3	1	*Peromyscus leucopus* (3)
		Summer 2021	1	1	*Peromyscus leucopus* (1)
		Autumn 2021	3	2	*Peromyscus leucopus* (2)
Darby	Control (Downstream)	Autumn 2020	2	1	*Peromyscus leucopus* (2)
		Summer 2021	3	1	*Peromyscus leucopus* (3)
		Autumn 2021	4	1	*Peromyscus leucopus* (4)
	Control (Upstream)	Autumn 2020	7	2	*Peromyscus leucopus* (5)
		Summer 2021	3	2	*Peromyscus leucopus* (2)
		Autumn 2021	14	1	*Peromyscus leucopus* (14)
Redick	Control (Downstream)	Autumn 2020	2	1	*Peromyscus leucopus* (2)
		Summer 2021	2	1	*Peromyscus leucopus* (2)
		Autumn 2021	5	2	*Peromyscus leucopus* (4)
	Control (Upstream)	Autumn 2020	-	-	-
		Summer 2021	5	1	*Peromyscus leucopus* (5)
		Autumn 2021	-	-	-

Camera Trapping						
	Adena	Lit	Spring 2021	23	1	*Odocoileus virginianus* (23)
			Summer 2021	34	4	*Odocoileus virginianus* (23)
			Autumn 2021	51	4	*Odocoileus virginianus* (47)
			Winter 2022	16	3	*Odocoileus virginianus* (12)
		Unlit	Spring 2021	23	2	*Sciurus carolinensis* (16)
			Summer 2021	23	3	*Odocoileus virginianus* (21)
			Autumn 2021	1	1	*Odocoileus virginianus* (1)
			Winter 2022	-	-	-
	Bill Moose	Lit	Spring 2021	57	2	*Procyon lotor* (38)
			Summer 2021	36	2	*Procyon lotor* (21)
			Autumn 2021	35	2	*Odocoileus virginianus* (34)
			Winter 2022	20	4	*Odocoileus virginianus* (15)
		Unlit	Spring 2021	9	2	*Odocoileus virginianus* (7)
			Summer 2021	35	3	*Odocoileus virginianus* (21)
			Autumn 2021	3	2	*Odocoileus virginianus* (2)
			Winter 2022	33	1	*Odocoileus virginianus* (33)
	Cosgray	Lit	Spring 2021	2	2	*Odocoileus virginianus* (1)/ *Tamias striatus* (1)
			Summer 2021	-	-	-
			Autumn 2021	6	2	*Sciurus carolinensis (5)*
			Winter 2022	7	3	*Canis latrans* (4)
		Unlit	Spring 2021	15	3	*Sciurus carolinensis (7)*
			Summer 2021	12	4	*Marmota monax* (5)/ *Procyon lotor* (5)
			Autumn 2021	8	4	*Odocoileus virginianus* (3)/ *Sciurus carolinensis* (3)
			Winter 2022	14	3	*Sciurus carolinensis (8)*
	Dublin Rec	Lit	Spring 2021	4	2	*Odocoileus virginianus* (3)
			Summer 2021	6	2	*Odocoileus virginianus* (5)
			Autumn 2021	13	2	*Odocoileus virginianus* (11)
			Winter 2022	1	1	*Sciurus carolinensis (1)*
		Unlit	Spring 2021	11	3	*Odocoileus virginianus* (6)
			Summer 2021	20	5	*Sylvilagus floridanus* (8)
			Autumn 2021	12	1	*Odocoileus virginianus* (12)
			Winter 2022	-	-	-
	Grove City	Lit	Spring 2021	49	5	*Procyon lotor* (25)
			Summer 2021	41	7	*Procyon lotor* (23)
			Autumn 2021	100	7	*Sciurus carolinensis* (61)
			Winter 2022	33	6	*Procyon lotor* (12)
		Unlit	Spring 2021	5	2	*Procyon lotor* (3)
			Summer 2021	134	9	*Procyon lotor* (46)

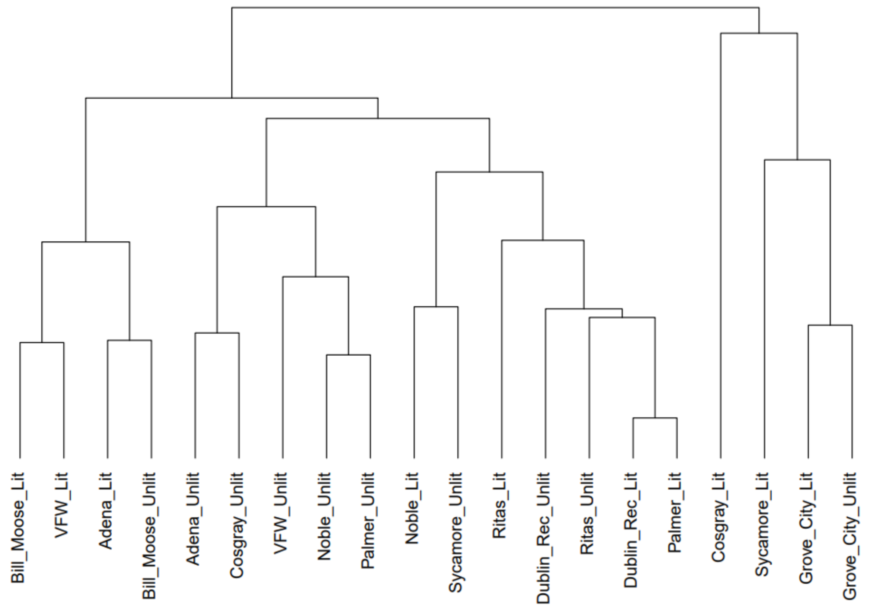
		Autumn 2021	66	4	*Sciurus carolinensis* (36)
		Winter 2022	10	4	*Sciurus carolinensis* (4)/ *Vulpes vulpes* (4)
Noble	Lit	Spring 2021	17	2	*Odocoileus virginianus* (16)
		Summer 2021	16	3	*Odocoileus virginianus* (13)
		Autumn 2021	13	4	*Vulpes vulpes* (5)
		Winter 2022	6	3	*Vulpes vulpes* (4)
	Unlit	Spring 2021	7	2	*Odocoileus virginianus* (5)
		Summer 2021	7	5	*Procyon lotor* (3)
		Autumn 2021	72	8	*Sciurus carolinensis* (42)
		Winter 2022	7	3	*Odocoileus virginianus* (3)/ *Procyon lotor* (3)
Palmer	Lit	Spring 2021	1	1	*Odocoileus virginianus* (1)
		Summer 2021	3	1	*Odocoileus virginianus* (3)
		Autumn 2021	15	2	*Odocoileus virginianus* (14)
		Winter 2022	3	2	*Odocoileus virginianus* (2)
	Unlit	Spring 2021	17	4	*Odocoileus virginianus* (6)/ *Procyon lotor* (6)
		Summer 2021	50	5	*Sciurus carolinensis* (19)
		Autumn 2021	15	4	*Sciurus carolinensis* (6)
		Winter 2022	13	5	*Sciurus carolinensis* (7)
Rita's	Lit	Spring 2021	1	1	*Odocoileus virginianus* (1)
		Summer 2021	14	2	*Procyon lotor* (10)
		Autumn 2021	12	1	*Odocoileus virginianus* (12)
		Winter 2022	17	2	*Procyon lotor* (14)
	Unlit	Spring 2021	9	1	*Odocoileus virginianus* (9)
		Summer 2021	11	4	*Odocoileus virginianus* (4)
		Autumn 2021	3	2	*Sciurus carolinensis* (2)
		Winter 2022	1	1	*Sciurus carolinensis* (1)
Sycamore	Lit	Spring 2021	6	1	*Sciurus carolinensis* (6)
		Summer 2021	23	6	*Sciurus carolinensis* (13)
		Autumn 2021	126	6	*Sciurus carolinensis* (102)
		Winter 2022	53	7	*Sciurus carolinensis* (26)
	Unlit	Spring 2021	1	1	*Sciurus carolinensis* (1)
		Summer 2021	3	1	*Odocoileus virginianus* (3)
		Autumn 2021	16	2	*Odocoileus virginianus* (8)/ *Sciurus carolinensis* (8)
		Winter 2022	41	3	*Odocoileus virginianus* (33)
VFW	Lit	Spring 2021	15	2	*Odocoileus virginianus* (8)
		Summer 2021	39	2	*Procyon lotor* (39)
		Autumn 2021	33	5	*Odocoileus virginianus* (13)
		Winter 2022	37	5	*Odocoileus virginianus* (10)/ *Procyon lotor* (10)/ *Vulpes vulpes* (10)
	Unlit	Spring 2021	27	7	*Sciurus carolinensis* (8)
		Summer 2021	47	7	*Odocoileus virginianus* (18)

		Autumn 2021	51	6	*Sciurus carolinensis* (17)
		Winter 2022	19	5	*Vulpes vulpes* (10)
Darby	Control (Downstream)	Spring 2021	8	1	*Odocoileus virginianus* (8)
		Summer 2021	12	2	*Odocoileus virginianus* (11)
		Autumn 2021	29	4	*Odocoileus virginianus* (14)
		Winter 2022	19	4	*Odocoileus virginianus* (6)
	Control (Upstream)	Spring 2021	12	2	*Odocoileus virginianus* (7)
		Summer 2021	7	2	*Odocoileus virginianus* (6)
		Autumn 2021	7	1	*Odocoileus virginianus* (7)
		Winter 2022	7	1	*Odocoileus virginianus* (11)
Redick	Control (Downstream)	Spring 2021	20	2	*Odocoileus virginianus* (15)
		Summer 2021	3	2	*Odocoileus virginianus* (2)
		Autumn 2021	20	4	*Sciurus carolinensis* (9)
		Winter 2022	33	6	*Odocoileus virginianus* (22)
	Control (Upstream)	Spring 2021	13	2	*Odocoileus virginianus* (12)
		Summer 2021	12	5	*Sciurus carolinensis* (6)
		Autumn 2021	25	3	*Sciurus carolinensis* (13)
		Winter 2022	17	4	*Odocoileus virginianus* (10)

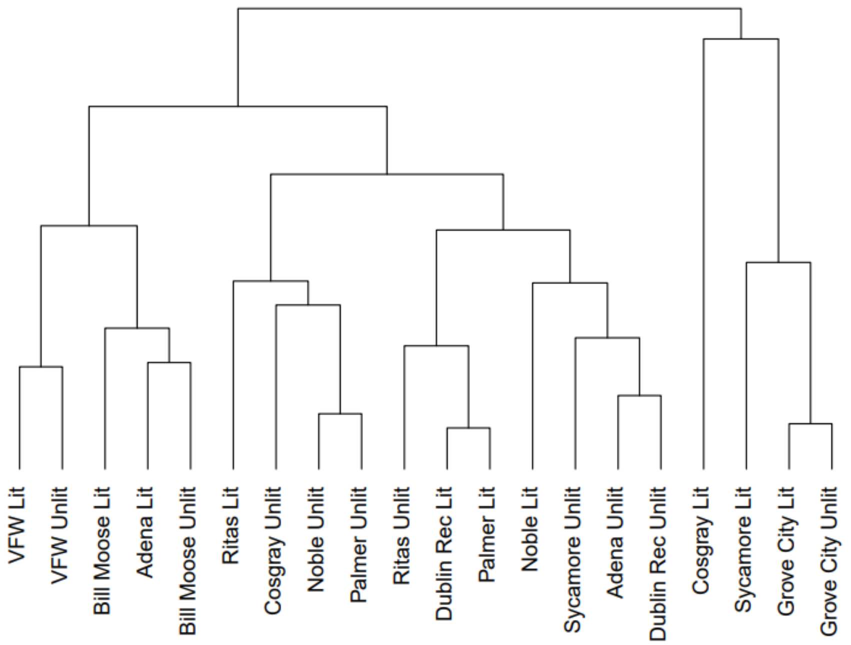
Appendix D: Bray-Curtis dissimilarity dendrograms for small mammal captures (top), total camera-trap encounters (middle), and camera-trap guild encounters (bottom). Sites closer together in the hierarchical tree are more similar (smaller Bray-Curtis distance) than sites that are farther apart. For the small mammal captures, Bill Moose and Noble never recorded a capture, placing them together on the left side of the chart.



Sites clustered by Bray−Curtis similarity of Small Mammal Captures



Sites clustered by Bray−Curtis similarity of Camera Trap Encounters



Sites clustered by Bray−Curtis similarity of Camera Trap Guild Encounters

Appendix E: All isotope samples used, broken down by sample type, site, reach, and category. $\delta^{13}C$ (‰) values are reported relative to Vienna Pee Dee Belemnite x 1000 while $\delta^{15}N$ (‰) are reported relative to atmospheric air x 1000.

Site	Reach	ID	Isotope Category	Date Sampled	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Mammal Hair Samples						
Adena	Lit	BLBR1	*Blarina brevicauda*	7/31/2021	-24.1	5.6
Darby	Upstream	BLBR1	*Blarina brevicauda*	7/2/2021	-24.1	7.6
Palmer	Lit	BLBR1	*Blarina brevicauda*	10/16/2020	-26.37	4.18
Palmer	Lit	DIVI2	*Didelphis virginiana*	8/3/2021	-22.4	7.8
Palmer	Lit	DIVI1	*Didelphis virginiana*	8/3/2021	-22.4	7.5
Adena	Lit	PEsp4	*Peromyscus*	8/19/2020	-23.05	6.58
Adena	Lit	PEsp3	*Peromyscus*	8/17/2020	-23.28	7.11
Adena	Lit	PEsp2	*Peromyscus*	8/17/2020	-23.56	6.29
Adena	Lit	PEsp1	*Peromyscus*	8/17/2020	-23.69	6.01
Adena	Lit	PELE1	*Peromyscus*	6/16/2021	-23.6	6.2
Adena	Unlit	PEsp3	*Peromyscus*	8/17/2020	-23.71	5.26
Adena	Unlit	PEsp1	*Peromyscus*	8/17/2020	-24.71	4.84
Adena	Unlit	PEsp2	*Peromyscus*	8/17/2020	-23.46	6.39
Adena	Unlit	PEsp4	*Peromyscus*	8/17/2020	-23.6	5.44
Adena	Unlit	PEMA1	*Peromyscus*	6/16/2021	-24.4	6.1
Adena	Unlit	PEMA2	*Peromyscus*	6/18/2021	-23.1	5.6
Adena	Unlit	PELE2	*Peromyscus*	6/16/2021	-22.6	7
Adena	Unlit	PELE1	*Peromyscus*	6/16/2021	-20.9	7
Bill Moose	Unlit	PEsp1	*Peromyscus*	8/22/2020	-19.79	7.53
Cosgray	Lit	PELE3	*Peromyscus*	6/25/2021	-23.3	5.3
Cosgray	Lit	PELE1	*Peromyscus*	6/25/2021	-23.7	4.1
Cosgray	Lit	PELE2	*Peromyscus*	6/25/2021	-23.8	5.5
Cosgray	Unlit	PEsp1	*Peromyscus*	9/3/2020	-23.12	6.77
Cosgray	Unlit	PELE3	*Peromyscus*	6/26/2021	-23.8	7.1
Cosgray	Unlit	PELE1	*Peromyscus*	6/25/2021	-23.8	4.6
Cosgray	Unlit	PELE2	*Peromyscus*	6/25/2021	-23.7	7.1
Darby	Downstream	PEsp1	*Peromyscus*	10/10/2020	-25.11	5.48
Darby	Downstream	PEsp2	*Peromyscus*	10/11/2020	-24.92	5.51
Darby	Downstream	PELE3	*Peromyscus*	7/1/2021	-24.5	5.6
Darby	Downstream	PELE1	*Peromyscus*	6/30/2021	-23.6	6.9
Darby	Downstream	PELE2	*Peromyscus*	6/30/2021	-23.6	6.4
Darby	Upstream	PEsp5	*Peromyscus*	10/10/2020	-24.98	5.56
Darby	Upstream	PEsp7	*Peromyscus*	10/11/2020	-24.87	5.09
Darby	Upstream	PEsp3	*Peromyscus*	10/9/2020	-25.01	5.09
Darby	Upstream	PEsp2	*Peromyscus*	10/9/2020	-23.69	5.54
Darby	Upstream	PEsp1	*Peromyscus*	10/9/2020	-25.24	3.78
Darby	Upstream	PEsp4	*Peromyscus*	10/10/2020	-23.03	4.16

Darby	Upstream	PEsp6	*Peromyscus*	10/11/2020	-24.33	5.05
Darby	Upstream	PELE1	*Peromyscus*	6/30/2021	-24.5	3.4
Dublin Rec	Lit	PEsp1	*Peromyscus*	8/27/2020	-24.89	6.39
Dublin Rec	Lit	PELE1	*Peromyscus*	6/21/2021	-24.1	6.3
Dublin Rec	Unlit	PEsp2	*Peromyscus*	8/27/2020	-22.22	6.67
Dublin Rec	Unlit	PEsp6	*Peromyscus*	8/29/2020	-22.27	6.32
Dublin Rec	Unlit	PEsp4	*Peromyscus*	8/27/2020	-24.89	4.27
Dublin Rec	Unlit	PEsp1	*Peromyscus*	8/27/2020	-23.77	6.17
Dublin Rec	Unlit	PEsp5	*Peromyscus*	8/28/2020	-23.34	6.16
Dublin Rec	Unlit	PEsp1	*Peromyscus*	8/27/2020	-25.24	7.3
Dublin Rec	Unlit	PELE1	*Peromyscus*	6/22/2021	-23	6
Dublin Rec	Unlit	PEMA1	*Peromyscus*	6/23/2021	-22.8	7
Grove City	Lit	PELE2	*Peromyscus*	7/16/2021	-23	6.2
Grove City	Lit	PELE1	*Peromyscus*	7/15/2021	-24	6.7
Grove City	Unlit	PELE1	*Peromyscus*	10/23/2020	-21.73	7.27
Grove City	Unlit	PELE3	*Peromyscus*	7/17/2021	-23.4	7.5
Grove City	Unlit	PELE1	*Peromyscus*	7/15/2021	-22.9	7.2
Grove City	Unlit	PELE2	*Peromyscus*	7/16/2021	-24.9	7.5
Noble	Unlit	PELE2	*Peromyscus*	7/10/2021	-23.1	2.9
Noble	Unlit	PEMA1	*Peromyscus*	7/12/2021	-23.5	8.5
Noble	Unlit	PELE3	*Peromyscus*	7/10/2021	-23.9	3.9
Noble	Unlit	PELE1	*Peromyscus*	7/10/2021	-20.9	6.7
Palmer	Lit	PELE1	*Peromyscus*	10/15/2020	-23.92	4.16
Palmer	Lit	PELE2	*Peromyscus*	8/3/2021	-24.7	5.4
Palmer	Lit	PELE1	*Peromyscus*	8/2/2021	-24.1	6
Palmer	Unlit	PELE1	*Peromyscus*	10/15/2020	-25.79	4.74
Palmer	Unlit	PELE2	*Peromyscus*	10/17/2020	-24.99	5.04
Palmer	Unlit	PELE3	*Peromyscus*	8/2/2021	-24.7	6.1
Palmer	Unlit	PELE1	*Peromyscus*	8/2/2021	-24	5.7
Palmer	Unlit	PELE2	*Peromyscus*	8/2/2021	-25	4.6
Palmer	Unlit	PELE5	*Peromyscus*	8/2/2021	-22.2	6.6
Palmer	Unlit	PELE4	*Peromyscus*	8/2/2021	-24.6	4.9
Palmer	Unlit	PEMA1	*Peromyscus*	8/3/2021	-25.2	5
Redick	Downstream	PEsp1	*Peromyscus*	9/20/2020	-22.96	5.5
Redick	Downstream	PELE1	*Peromyscus*	7/7/2021	-23.2	5
Redick	Downstream	PELE2	*Peromyscus*	7/8/2021	-20.9	7.3
Redick	Upstream	PELE1	*Peromyscus*	7/6/2021	-22.9	10.9
Redick	Upstream	PELE3	*Peromyscus*	7/8/2021	-23.7	3.6
Redick	Upstream	PELE2	*Peromyscus*	7/6/2021	-22.8	3.5
Rita's	Lit	PEsp1	*Peromyscus*	9/30/2020	-22.07	4.92
Rita's	Lit	PELE6	*Peromyscus*	7/29/2021	-21.7	6.7
Rita's	Lit	PELE2	*Peromyscus*	7/29/2021	-22.8	5.3
Rita's	Lit	PELE1	*Peromyscus*	7/29/2021	-22.9	7.6
Rita's	Lit	PELE8	*Peromyscus*	7/29/2021	-23.2	6

Rita's	Lit	PELE4	*Peromyscus*	7/29/2021	-20	6.1
Rita's	Lit	PELE5	*Peromyscus*	7/29/2021	-23.1	6.8
Rita's	Lit	PELE3	*Peromyscus*	7/29/2021	-22	7
Rita's	Lit	PELE10	*Peromyscus*	7/30/2021	-23.2	5.4
Rita's	Lit	PELE7	*Peromyscus*	7/29/2021	-23.3	4.9
Rita's	Lit	PELE9	*Peromyscus*	7/30/2021	-19.8	7.1
Rita's	Unlit	PEsp1	*Peromyscus*	9/30/2020	-22.39	6.85
Rita's	Unlit	PEsp4	*Peromyscus*	9/30/2020	-23.01	4.89
Rita's	Unlit	PEsp3	*Peromyscus*	9/30/2020	-21.36	6.5
Rita's	Unlit	PEsp2	*Peromyscus*	9/30/2020	-23.91	6.34
Rita's	Unlit	PELE6	*Peromyscus*	7/31/2021	-24	5.8
Rita's	Unlit	PELE3	*Peromyscus*	7/29/2021	-23.1	6
Rita's	Unlit	PELE1	*Peromyscus*	7/29/2021	-24.1	4.6
Rita's	Unlit	PELE2	*Peromyscus*	7/29/2021	-24.3	5.2
Rita's	Unlit	PELE5	*Peromyscus*	7/30/2021	-23	6
Rita's	Unlit	PELE4	*Peromyscus*	7/30/2021	-23.4	5.6
Sycamore	Lit	PEsp1	*Peromyscus*	9/16/2020	-25.86	4.98
Sycamore	Lit	PELE1	*Peromyscus*	6/8/2021	-23.5	3.5
Sycamore	Unlit	PEsp3	*Peromyscus*	9/17/2020	-22.95	7.41
Sycamore	Unlit	PEsp2	*Peromyscus*	9/16/2020	-20.73	6.13
Sycamore	Unlit	Pesp1	*Peromyscus*	9/16/2020	-21.57	7.6
Sycamore	Unlit	PELE1	*Peromyscus*	6/10/2021	-22.9	4.3
VFW	Lit	PEsp1	*Peromyscus*	10/5/2020	-23.66	5.26
VFW	Lit	PELE1	*Peromyscus*	8/8/2021	-22.9	5.2
VFW	Unlit	PEsp1	*Peromyscus*	10/5/2020	-23.92	5.61
VFW	Unlit	PEsp3	*Peromyscus*	10/5/2020	-23.07	6.31
VFW	Unlit	PEsp2	*Peromyscus*	10/5/2020	-26.83	4.31
VFW	Unlit	PELE1	*Peromyscus*	8/6/2021	-22.9	6.6
Adena	Lit	TAST1	*Tamias striatus*	6/17/2021	-23.1	4.8
Bill Moose	Lit	TAST1	*Tamias striatus*	6/12/2021	-23.3	7.4
Cosgray	Lit	TAST1	*Tamias striatus*	6/25/2021	-22.7	5.5
Cosgray	Lit	TAST2	*Tamias striatus*	6/27/2021	-22.5	3.5
Dublin Rec	Lit	TAST1	*Tamias striatus*	6/21/2021	-23.8	8.5
Dublin Rec	Unlit	TAST1	*Tamias striatus*	6/21/2021	-21.6	6.2
Palmer	Lit	TAST1	*Tamias striatus*	10/15/2020	-23.17	4.77
VFW	Lit	TAST1	*Tamias striatus*	8/7/2021	-23	5.4
Terrestrial Vegetation Samples						
Adena	Lit	shrub 1	Fruits and Nuts	8/18/2020	-32.12	0.01
Adena	Lit	tree 1	Fruits and Nuts	8/18/2020	-29.06	1.98
Adena	Unlit	shrub 1	Fruits and Nuts	8/18/2020	-33.57	-2.13
Adena	Unlit	tree 1	Fruits and Nuts	8/18/2020	-26.17	-1.13
Bill Moose	Lit	tree 1	Fruits and Nuts	8/22/2020	-28.45	0.08
Bill Moose	Lit	shrub 1	Fruits and Nuts	8/22/2020	-33.72	-0.42
Bill Moose	Unlit	tree 1	Fruits and Nuts	8/22/2020	-24.34	-0.76

Bill Moose	Unlit	shrub 1	Fruits and Nuts	8/22/2020	-34.35	-3.69
Cosgray	Unlit	s shrub	Fruits and Nuts	6/26/2021	-32.12	2.26
Cosgray	Lit	shrub 1	Fruits and Nuts	9/2/2020	-29.53	0.44
Cosgray	Lit	shrub 2	Fruits and Nuts	9/2/2020	-31.69	-1.11
Cosgray	Unlit	shrub 1	Fruits and Nuts	9/2/2020	-33.29	-2.12
Cosgray	Unlit	shrub 2	Fruits and Nuts	9/2/2020	-32.55	0.3
Darby	Downstream	tree 1	Fruits and Nuts	10/9/2020	-28.77	-4.01
Darby	Downstream	shrub 1	Fruits and Nuts	10/9/2020	-30.34	-1.12
Darby	Upstream	shrub 1	Fruits and Nuts	10/9/2020	-29.99	0.31
Darby	Upstream	tree 1	Fruits and Nuts	10/9/2020	-24.66	-0.07
Dublin Rec	Lit	s shrub	Fruits and Nuts	6/21/2021	-30.91	1.04
Dublin Rec	Lit	shrub 1	Fruits and Nuts	8/28/2020	-31.79	1.08
Dublin Rec	Lit	tree 1	Fruits and Nuts	8/28/2020	-28.24	0.32
Dublin Rec	Unlit	shrub 1	Fruits and Nuts	8/28/2020	-30.77	2.06
Dublin Rec	Unlit	tree 1	Fruits and Nuts	8/28/2020	-28.12	3.83
Grove City	Lit	shrub 1	Fruits and Nuts	10/23/2020	-29.18	-0.85
Grove City	Lit	tree 1	Fruits and Nuts	10/23/2020	-27.27	4.19
Grove City	Unlit	shrub 1	Fruits and Nuts	10/23/2020	-33.43	0.93
Noble	Lit	s shrub	Fruits and Nuts	7/10/2021	-31.97	-3.34
Noble	Lit	shrub 1	Fruits and Nuts	9/26/2020	-33.45	-4
Noble	Lit	tree 1	Fruits and Nuts	9/26/2020	-27.13	-2.28
Noble	Lit	s tree	Fruits and Nuts	7/10/2021	-25.14	0.41
Noble	Unlit	tree 1	Fruits and Nuts	9/26/2020	-24.81	-1.23
Noble	Unlit	s shrub	Fruits and Nuts	7/10/2021	-32.96	-3.91
Palmer	Lit	shrub 1	Fruits and Nuts	10/16/2020	-33.69	0.6
Palmer	Unlit	shrub 1	Fruits and Nuts	10/16/2020	-34.37	-0.66
Redick	Downstream	shrub 1	Fruits and Nuts	9/21/2020	-32.88	-1.83
Redick	Downstream	s tree	Fruits and Nuts	7/6/2021	-29.6	-1.87
Redick	Downstream	tree 1	Fruits and Nuts	9/21/2020	-27.95	-0.26
Redick	Downstream	tree 2	Fruits and Nuts	9/21/2020	-28.51	-0.91
Redick	Upstream	shrub 1	Fruits and Nuts	9/21/2020	-33.6	-4.45
Redick	Upstream	s tree	Fruits and Nuts	7/6/2021	-29.59	-0.53
Redick	Upstream	tree 1	Fruits and Nuts	9/21/2020	-29.99	-1.02
Redick	Upstream	tree 2	Fruits and Nuts	9/21/2020	-29.72	-0.54
Rita's	Lit	tree 1	Fruits and Nuts	9/30/2020	-28.22	-0.29
Rita's	Lit	shrub 1	Fruits and Nuts	9/30/2020	-31.77	-1.33
Rita's	Unlit	shrub 1	Fruits and Nuts	9/30/2020	-31.1	1.95
Rita's	Unlit	tree 1	Fruits and Nuts	9/30/2020	-27.27	2.46
Sycamore	Lit	tree 1	Fruits and Nuts	9/17/2020	-28.17	-1.21
Sycamore	Lit	shrub 1	Fruits and Nuts	9/17/2020	-30.68	-0.08
Sycamore	Unlit	tree 1	Fruits and Nuts	9/17/2020	-30.23	0
Sycamore	Unlit	shrub 1	Fruits and Nuts	9/17/2020	-30.6	-2.65
VFW	Lit	shrub 1	Fruits and Nuts	10/5/2020	-33.71	0.18
VFW	Lit	tree 1	Fruits and Nuts	10/5/2020	-27.77	1.09

VFW	Unlit	shrub 1	Fruits and Nuts	10/5/2020	-34.24	0.97
VFW	Unlit	tree 1	Fruits and Nuts	10/5/2020	-27.99	1.74
Adena	Lit	grass 1	Vegetation	8/18/2020	-31.22	-0.14
Adena	Lit	s grass	Vegetation	6/16/2021	-31.03	0.14
Adena	Lit	forb 1	Vegetation	8/18/2020	-33.85	2.46
Adena	Lit	forb 2	Vegetation	8/18/2020	-33.63	4.99
Adena	Unlit	forb 2	Vegetation	8/18/2020	-33.49	-2.54
Adena	Unlit	forb 1	Vegetation	8/18/2020	-32.26	-3.39
Bill Moose	Lit	grass 1	Vegetation	8/22/2020	-31.69	1.19
Bill Moose	Lit	forb 2	Vegetation	8/22/2020	-32.74	-0.53
Bill Moose	Lit	forb 1	Vegetation	8/22/2020	-32.01	0.69
Bill Moose	Unlit	s grass	Vegetation	6/13/2021	-34.09	-0.04
Bill Moose	Unlit	forb 2	Vegetation	8/22/2020	-33.92	-0.55
Bill Moose	Unlit	forb 1	Vegetation	8/22/2020	-31.64	-0.93
Bill Moose	Unlit	grass 1	Vegetation	8/22/2020	-32.68	-0.87
Bill Moose	Unlit	s forb	Vegetation	6/13/2021	-32.25	-0.25
Cosgray	Lit	grass 1	Vegetation	9/2/2020	-31.02	6.59
Cosgray	Lit	forb 1	Vegetation	9/2/2020	-33.4	6.03
Cosgray	Lit	s grass	Vegetation	6/26/2021	-30.73	4.64
Cosgray	Unlit	s forb	Vegetation	6/26/2021	-30.43	0.12
Cosgray	Unlit	grass 1	Vegetation	9/2/2020	-33.87	2.35
Darby	Downstream	grass 2	Vegetation	10/9/2020	-31.24	5.43
Darby	Downstream	grass 1	Vegetation	10/9/2020	-33.03	2.86
Darby	Downstream	forb 1	Vegetation	10/9/2020	-33.54	8.3
Darby	Upstream	grass 1	Vegetation	10/9/2020	-31.13	14.64
Darby	Upstream	forb 1	Vegetation	10/9/2020	-33.31	7.77
Darby	Upstream	grass 2	Vegetation	10/9/2020	-28.18	4.72
Darby	Upstream	s forb	Vegetation	6/30/2021	-27.01	-0.4
Dublin Rec	Lit	forb 1	Vegetation	8/28/2020	-30.29	2.64
Dublin Rec	Lit	grass 2	Vegetation	8/28/2020	-30.7	2.22
Dublin Rec	Lit	grass 1	Vegetation	8/28/2020	-32.26	0.97
Dublin Rec	Lit	s forb	Vegetation	6/21/2021	-31.55	3.83
Dublin Rec	Unlit	grass 2	Vegetation	8/28/2020	-31.47	3.72
Dublin Rec	Unlit	forb 1	Vegetation	8/28/2020	-32.47	3.65
Dublin Rec	Unlit	grass 1	Vegetation	8/28/2020	-31.25	9.72
Grove City	Lit	grass 1	Vegetation	10/23/2020	-29.06	0.87
Grove City	Lit	forb 1	Vegetation	10/23/2020	-28.93	-0.16
Grove City	Unlit	grass 1	Vegetation	10/23/2020	-34.47	4.96
Grove City	Unlit	forb 1	Vegetation	10/23/2020	-32.72	6.21
Noble	Lit	forb 1	Vegetation	9/26/2020	-34.46	-1.69
Noble	Lit	grass 1	Vegetation	9/26/2020	-33.53	0.11
Noble	Lit	s forb	Vegetation	7/10/2021	-34.83	0
Noble	Unlit	s grass	Vegetation	7/10/2021	-35.05	-2.78
Noble	Unlit	grass 1	Vegetation	9/26/2020	-32.08	-3.85

Noble	Unlit	forb 1	Vegetation	9/26/2020	-33.54	-2.66
Palmer	Lit	grass 1	Vegetation	10/16/2020	-32.73	-1.59
Palmer	Lit	forb 2	Vegetation	10/16/2020	-34.57	-3.37
Palmer	Lit	forb 1	Vegetation	10/15/2020	-33.18	-1.81
Palmer	Unlit	forb 1	Vegetation	10/16/2020	-35.45	-0.6
Palmer	Unlit	forb 2	Vegetation	10/16/2020	-35.32	0.43
Palmer	Unlit	grass 1	Vegetation	10/16/2020	-32.62	1.07
Redick	Downstream	forb 1	Vegetation	9/21/2020	-32.4	-1.4
Redick	Upstream	forb 1	Vegetation	9/21/2020	-34.46	-0.12
Redick	Upstream	grass 1	Vegetation	9/21/2020	-32.7	-1.21
Rita's	Lit	grass 1	Vegetation	9/30/2020	-33.03	1.12
Rita's	Lit	forb 1	Vegetation	9/30/2020	-33.02	1.23
Rita's	Unlit	forb 1	Vegetation	9/30/2020	-35.33	2.04
Rita's	Unlit	grass 1	Vegetation	9/30/2020	-32.72	0.12
Sycamore	Lit	grass 1	Vegetation	9/17/2020	-30.22	3.21
Sycamore	Lit	forb 1	Vegetation	9/17/2020	-30.93	1.39
Sycamore	Unlit	grass 1	Vegetation	9/17/2020	-31.26	5.22
Sycamore	Unlit	forb 1	Vegetation	9/17/2020	-31.89	2.2
VFW	Lit	forb 1	Vegetation	10/5/2020	-32.75	-0.11
VFW	Lit	grass 1	Vegetation	10/5/2020	-32.82	0.16
VFW	Lit	grass 2	Vegetation	10/5/2020	-33.04	-1.9
VFW	Unlit	forb 1	Vegetation	10/5/2020	-33.16	0
VFW	Unlit	grass 2	Vegetation	10/5/2020	-30.85	0.58
VFW	Unlit	grass 1	Vegetation	10/5/2020	-33.69	-3.32
	Periphyton Samples					
Adena	Lit	P321	Periphyton	7/16/2020	-27.55	-0.09
Adena	Lit	P350	Periphyton	7/16/2020	-26.32	5.24
Adena	Lit	P400	Periphyton	1/18/2021	-21.59	6.15
Adena	Lit	P401	Periphyton	1/18/2021	-32.71	6.24
Adena	Lit	P402	Periphyton	1/18/2021	-31.36	5.92
Adena	Unlit	P326	Periphyton	7/16/2020	-26.35	4.35
Adena	Unlit	P351	Periphyton	7/16/2020	-26.41	5.76
Adena	Unlit	P403	Periphyton	1/18/2021	-26.05	6.52
Adena	Unlit	P404	Periphyton	1/18/2021	-19.09	5.74
Adena	Unlit	P405	Periphyton	1/18/2021	-23.81	6.81
Bill Moose	Lit	P329	Periphyton	7/16/2020	-28.92	5.15
Bill Moose	Lit	P347	Periphyton	7/16/2020	-26.81	5.1
Bill Moose	Lit	P354	Periphyton	7/16/2020	-28.59	2.45
Bill Moose	Lit	P406	Periphyton	1/18/2021	-18.62	4.13
Bill Moose	Lit	P407	Periphyton	1/18/2021	-25.18	4.58
Bill Moose	Lit	P408	Periphyton	1/18/2021	-24.49	6.18
Bill Moose	Unlit	P316	Periphyton	7/16/2020	-26.88	4.85
Bill Moose	Unlit	P356	Periphyton	7/16/2020	-27.68	3.95
Bill Moose	Unlit	P409	Periphyton	1/18/2021	-20.48	5.59

Bill Moose	Unlit	P410	Periphyton	1/18/2021	-27.65	5.68
Bill Moose	Unlit	P411	Periphyton	1/18/2021	-16.86	4.97
Cosgray	Lit	P335	Periphyton	7/24/2020	-30.76	5.06
Cosgray	Lit	P343	Periphyton	7/24/2020	-28.08	3.63
Cosgray	Lit	P361	Periphyton	7/24/2020	-26.8	6.82
Cosgray	Lit	P430	Periphyton	3/5/2021	-17.6	4.52
Cosgray	Lit	P431	Periphyton	3/5/2021	-17.86	3.33
Cosgray	Lit	P432	Periphyton	3/5/2021	-22.09	6.08
Cosgray	Unlit	P365	Periphyton	7/24/2020	-32.76	2.83
Cosgray	Unlit	P368	Periphyton	7/24/2020	-31.66	6.59
Cosgray	Unlit	P433	Periphyton	3/5/2021	-21.98	5.74
Cosgray	Unlit	P434	Periphyton	3/5/2021	-29.16	5.75
Cosgray	Unlit	P435	Periphyton	3/5/2021	-18.07	5.56
Darby	Downstream	P322	Periphyton	7/25/2020	-25.65	4.92
Darby	Downstream	P328	Periphyton	7/25/2020	-23.61	5.35
Darby	Downstream	P352	Periphyton	7/25/2020	-21.57	6.05
Darby	Downstream	P415	Periphyton	2/1/2021	-19.97	5.29
Darby	Downstream	P416	Periphyton	2/1/2021	-21.17	6.9
Darby	Downstream	P417	Periphyton	2/1/2021	-29.66	8.31
Darby	Upstream	P412	Periphyton	2/1/2021	-22.56	6.6
Darby	Upstream	P413	Periphyton	2/1/2021	-21.59	6.31
Darby	Upstream	P414	Periphyton	2/1/2021	-20.38	9.29
Darby	Upstream	P362	Periphyton	7/25/2020	-28.5	5.98
Darby	Upstream	P363	Periphyton	7/25/2020	-25.74	3.75
Darby	Upstream	P366	Periphyton	7/25/2020	-28.64	5.68
Dublin Rec	Lit	P418	Periphyton	2/3/2021	-21.58	10.56
Dublin Rec	Lit	P419	Periphyton	2/3/2021	-25.26	9.69
Dublin Rec	Lit	P420	Periphyton	2/3/2021	-32.25	8.45
Dublin Rec	Unlit	P421	Periphyton	2/3/2021	-30.56	10.67
Dublin Rec	Unlit	P422	Periphyton	2/3/2021	-32.07	7.59
Dublin Rec	Unlit	P423	Periphyton	2/3/2021	-32.41	7.68
Dublin Rec	Lit	P369	Periphyton	7/23/2020	-29.79	4.66
Dublin Rec	Unlit	P342	Periphyton	7/23/2020	-30.14	5.07
Grove City	Lit	P323	Periphyton	7/28/2020	-27.03	8.26
Grove City	Lit	P353	Periphyton	7/28/2020	-23.74	8.4
Grove City	Lit	P436	Periphyton	2/23/2021	-29.24	10.82
Grove City	Lit	P437	Periphyton	2/23/2021	-29.15	10.21
Grove City	Lit	P438	Periphyton	2/23/2021	-25.98	11.05
Grove City	Unlit	P319	Periphyton	7/28/2020	-16.43	6.37
Grove City	Unlit	P332	Periphyton	7/28/2020	-25.39	7.72
Grove City	Unlit	P439	Periphyton	2/23/2021	-26.17	9.25
Grove City	Unlit	P440	Periphyton	2/23/2021	-25.72	7.44
Grove City	Unlit	P441	Periphyton	2/23/2021	-25.79	4.27
Noble	Lit	P324	Periphyton	7/27/2020	-28.35	2.92

Noble	Lit	P325	Periphyton	7/27/2020	-26.63	5
Noble	Lit	P327	Periphyton	7/27/2020	-25.73	5.54
Noble	Lit	P370	Periphyton	1/21/2021	-22.71	6.55
Noble	Lit	P371	Periphyton	1/21/2021	-29.98	7.22
Noble	Lit	P372	Periphyton	1/21/2021	-29.45	6.68
Noble	Unlit	P318	Periphyton	7/27/2020	-23.73	3.76
Noble	Unlit	P346	Periphyton	7/27/2020	-22.97	5.26
Noble	Unlit	P373	Periphyton	1/21/2021	-20.77	5.99
Noble	Unlit	P374	Periphyton	1/21/2021	-31.36	6.75
Noble	Unlit	P375	Periphyton	1/21/2021	-30.51	6.93
Palmer	Lit	P336	Periphyton	7/6/2020	-26.48	3.59
Palmer	Lit	P340	Periphyton	7/6/2020	-7.43	5.2
Palmer	Lit	P358	Periphyton	7/6/2020	-28.77	0.56
Palmer	Lit	P376	Periphyton	1/13/2021	-27.54	8.29
Palmer	Lit	P377	Periphyton	1/13/2021	-23.06	7.35
Palmer	Lit	P378	Periphyton	1/13/2021	-25.62	8.96
Palmer	Unlit	P331	Periphyton	7/6/2020	-17.96	5.71
Palmer	Unlit	P359	Periphyton	7/6/2020	-28.14	-1.14
Palmer	Unlit	P364	Periphyton	7/6/2020	-28.74	7.07
Palmer	Unlit	P379	Periphyton	1/13/2021	-30.07	9.71
Palmer	Unlit	P380	Periphyton	1/13/2021	-23.56	8.1
Palmer	Unlit	P381	Periphyton	1/13/2021	-21.31	5.61
Redick	Downstream	P344	Periphyton	7/14/2020	-29.84	8.12
Redick	Downstream	P385	Periphyton	2/11/2021	-22.18	8.79
Redick	Downstream	P386	Periphyton	2/11/2021	-21.89	8.53
Redick	Downstream	P387	Periphyton	2/11/2021	-22.18	9.62
Redick	Upstream	P382	Periphyton	2/11/2021	-25.45	9.82
Redick	Upstream	P383	Periphyton	2/11/2021	-23.16	10.11
Redick	Upstream	P384	Periphyton	2/11/2021	-17.45	7.81
Redick	Upstream	P337	Periphyton	7/14/2020	-23.94	7.69
Redick	Upstream	P367	Periphyton	7/14/2020	-24.12	6.33
Rita's	Lit	P317	Periphyton	7/13/2020	-26.53	4.31
Rita's	Lit	P320	Periphyton	7/13/2020	-22.39	4.22
Rita's	Lit	P388	Periphyton	1/26/2021	-21.49	5.56
Rita's	Lit	P389	Periphyton	1/26/2021	-18.15	5.65
Rita's	Lit	P390	Periphyton	1/26/2021	-18.32	6.66
Rita's	Unlit	P345	Periphyton	7/13/2020	-28.48	5.21
Rita's	Unlit	P348	Periphyton	7/13/2020	-31.26	2.79
Rita's	Unlit	P349	Periphyton	7/13/2020	-26.92	4.81
Rita's	Unlit	P391	Periphyton	1/26/2021	-26.03	7.6
Rita's	Unlit	P392	Periphyton	1/26/2021	-22.04	8.01
Rita's	Unlit	P393	Periphyton	1/26/2021	-27.32	8.51
Sycamore	Lit	P330	Periphyton	7/10/2020	-21.13	9.39
Sycamore	Lit	P334	Periphyton	7/10/2020	-26.55	8.68

Sycamore	Lit	P355	Periphyton	7/10/2020	-29.15	5.51
Sycamore	Lit	P424	Periphyton	2/26/2021	-26.33	-3.67
Sycamore	Lit	P425	Periphyton	2/26/2021	-29.63	-6.27
Sycamore	Lit	P426	Periphyton	2/26/2021	-27.49	-7.8
Sycamore	Unlit	P333	Periphyton	7/10/2020	-25.27	8.89
Sycamore	Unlit	P341	Periphyton	7/10/2020	-24.65	9.63
Sycamore	Unlit	P360	Periphyton	7/10/2020	-23.5	8.72
Sycamore	Unlit	P427	Periphyton	2/26/2021	-24.09	-5.82
Sycamore	Unlit	P428	Periphyton	2/26/2021	-28.76	-9.06
Sycamore	Unlit	P429	Periphyton	2/26/2021	-23.67	-2.48
VFW	Lit	P338	Periphyton	7/15/2020	-27.51	0.15
VFW	Lit	P394	Periphyton	1/13/2021	-28.85	7.42
VFW	Lit	P395	Periphyton	1/13/2021	-20.54	6.6
VFW	Lit	P396	Periphyton	1/13/2021	-23.24	6.85
VFW	Unlit	P339	Periphyton	7/15/2020	-27.01	4.62
VFW	Unlit	P357	Periphyton	7/15/2020	-25.56	5.13
VFW	Unlit	P397	Periphyton	1/13/2021	-27.66	7.38
VFW	Unlit	P398	Periphyton	1/13/2021	-21.32	8.41
VFW	Unlit	P399	Periphyton	1/13/2021	-23.45	9.21
Aquatic Detritus Samples						
Adena	Lit	D269	Detritus	9/4/2019	-28.04	0.93
Adena	Lit	D296	Detritus	9/4/2019	-27.43	3.02
Adena	Lit	D306	Detritus	9/4/2019	-28.58	1.28
Adena	Lit	D460	Detritus	1/29/2020	-29.59	1.46
Adena	Lit	D461	Detritus	1/29/2020	-28.7	0.99
Adena	Lit	D462	Detritus	1/29/2020	-28.49	1.54
Adena	Lit	D525	Detritus	1/18/2021	-29.57	1.55
Adena	Lit	D526	Detritus	1/18/2021	-28.28	2.64
Adena	Lit	D527	Detritus	1/18/2021	-28.1	3.22
Adena	Lit	D651	Detritus	7/16/2020	-29.27	2.1
Adena	Lit	D652	Detritus	7/16/2020	-29	1.23
Adena	Lit	D653	Detritus	7/16/2020	-29.56	2.82
Adena	Unlit	D274	Detritus	9/4/2019	-28	2.11
Adena	Unlit	D299	Detritus	9/4/2019	-27.54	1.67
Adena	Unlit	D304	Detritus	9/4/2019	-28.36	2.61
Adena	Unlit	D463	Detritus	1/29/2020	-29.2	1.41
Adena	Unlit	D464	Detritus	1/29/2020	-28.63	0.59
Adena	Unlit	D528	Detritus	1/18/2021	-28.74	0.75
Adena	Unlit	D529	Detritus	1/18/2021	-29.22	0.33
Adena	Unlit	D530	Detritus	1/18/2021	-28.47	2.65
Adena	Unlit	D654	Detritus	7/16/2020	-28.61	2.61
Adena	Unlit	D655	Detritus	7/16/2020	-28.89	1.63
Adena	Unlit	D656	Detritus	7/16/2020	-28.84	1.95
Bill Moose	Lit	D252	Detritus	9/14/2019	-28.9	0.01

Bill Moose	Lit	D291	Detritus	9/14/2019	-29.32	2.4
Bill Moose	Lit	D313	Detritus	9/14/2019	-30.79	-0.29
Bill Moose	Lit	D444	Detritus	1/27/2020	-30.03	-0.91
Bill Moose	Lit	D451	Detritus	1/27/2020	-29.49	1.55
Bill Moose	Lit	D453	Detritus	1/27/2020	-29.41	0.35
Bill Moose	Lit	D531	Detritus	1/18/2021	-27.88	0.2
Bill Moose	Lit	D532	Detritus	1/18/2021	-27.37	-0.44
Bill Moose	Lit	D533	Detritus	1/18/2021	-28.51	-0.54
Bill Moose	Lit	D609	Detritus	7/16/2020	-27.7	-0.15
Bill Moose	Lit	D610	Detritus	7/16/2020	-28.25	-0.32
Bill Moose	Lit	D611	Detritus	7/16/2020	-29.27	2.15
Bill Moose	Unlit	D247	Detritus	9/14/2019	-27.66	-0.54
Bill Moose	Unlit	D308	Detritus	9/14/2019	-28.12	1.08
Bill Moose	Unlit	D310	Detritus	9/14/2019	-27.99	1.85
Bill Moose	Unlit	D443	Detritus	1/27/2020	-28.38	-2.69
Bill Moose	Unlit	D445	Detritus	1/27/2020	-28.96	-0.49
Bill Moose	Unlit	D452	Detritus	1/27/2020	-30.08	-0.54
Bill Moose	Unlit	D534	Detritus	1/18/2021	-27.92	-0.1
Bill Moose	Unlit	D535	Detritus	1/18/2021	-29.03	0.91
Bill Moose	Unlit	D536	Detritus	1/18/2021	-28.48	0.63
Bill Moose	Unlit	D612	Detritus	7/16/2020	-27.65	3.01
Bill Moose	Unlit	D613	Detritus	7/16/2020	-26.61	-0.24
Bill Moose	Unlit	D614	Detritus	7/16/2020	-27.8	0.38
Cosgray	Lit	D253	Detritus	9/5/2019	-29.25	3.58
Cosgray	Lit	D264	Detritus	9/5/2019	-28.46	0.37
Cosgray	Lit	D314	Detritus	9/5/2019	-31.14	3.68
Cosgray	Lit	D472	Detritus	2/3/2020	-29.86	2.01
Cosgray	Lit	D473	Detritus	2/3/2020	-29.19	1.81
Cosgray	Lit	D474	Detritus	2/3/2020	-30.06	2.4
Cosgray	Lit	D579	Detritus	3/5/2021	-28.24	3.5
Cosgray	Lit	D580	Detritus	3/5/2021	-30.39	2.87
Cosgray	Lit	D581	Detritus	3/5/2021	-29.33	4.81
Cosgray	Lit	D621	Detritus	7/24/2020	-27.57	3.27
Cosgray	Lit	D622	Detritus	7/24/2020	-27.63	3.41
Cosgray	Lit	D623	Detritus	7/24/2020	-28.07	2.59
Cosgray	Unlit	D249	Detritus	9/5/2019	-29.45	4.13
Cosgray	Unlit	D262	Detritus	9/5/2019	-30.1	1.42
Cosgray	Unlit	D268	Detritus	9/5/2019	-29.28	3.2
Cosgray	Unlit	D475	Detritus	2/3/2020	-29.84	2.19
Cosgray	Unlit	D476	Detritus	2/3/2020	-30.37	2.06
Cosgray	Unlit	D477	Detritus	2/3/2020	-29.83	1.9
Cosgray	Unlit	D582	Detritus	3/5/2021	-28.53	3.71
Cosgray	Unlit	D583	Detritus	3/5/2021	-27.47	3.43
Cosgray	Unlit	D584	Detritus	3/5/2021	-29.54	3.13

Cosgray	Unlit	D624	Detritus	7/24/2020	-28.51	2.91
Cosgray	Unlit	D625	Detritus	7/24/2020	-31.01	1.86
Cosgray	Unlit	D626	Detritus	7/24/2020	-28.89	3.85
Darby	Downstream	D263	Detritus	9/9/2019	-28.62	0.23
Darby	Downstream	D270	Detritus	9/9/2019	-28.72	0.61
Darby	Downstream	D295	Detritus	9/9/2019	-29.44	1.17
Darby	Downstream	D496	Detritus	2/21/2020	-28.81	1.73
Darby	Downstream	D497	Detritus	2/21/2020	-29.23	0.39
Darby	Downstream	D498	Detritus	2/21/2020	-29.19	1.78
Darby	Downstream	D552	Detritus	2/1/2021	-29.57	1.2
Darby	Downstream	D553	Detritus	2/1/2021	-28.65	2.75
Darby	Downstream	D554	Detritus	2/1/2021	-28.3	3.36
Darby	Downstream	D630	Detritus	7/25/2020	-29.68	-0.88
Darby	Downstream	D631	Detritus	7/25/2020	-28	0.79
Darby	Downstream	D632	Detritus	7/25/2020	-28.75	1.41
Darby	Upstream	D245	Detritus	9/9/2019	-28.36	1.66
Darby	Upstream	D276	Detritus	9/9/2019	-29.11	0.94
Darby	Upstream	D280	Detritus	9/9/2019	-28.73	0.82
Darby	Upstream	D499	Detritus	2/21/2020	-28.97	2.51
Darby	Upstream	D500	Detritus	2/21/2020	-29.22	1.98
Darby	Upstream	D501	Detritus	2/21/2020	-28.38	1.68
Darby	Upstream	D549	Detritus	2/1/2021	-28.79	2.64
Darby	Upstream	D550	Detritus	2/1/2021	-27.06	4.53
Darby	Upstream	D551	Detritus	2/1/2021	-27.61	0.64
Darby	Upstream	D627	Detritus	7/25/2020	-28.6	3.93
Darby	Upstream	D628	Detritus	7/25/2020	-29.04	0.83
Darby	Upstream	D629	Detritus	7/25/2020	-30.56	0.19
Dublin Rec	Lit	D258	Detritus	9/5/2019	-29.2	5.85
Dublin Rec	Lit	D265	Detritus	9/5/2019	-29.21	5.08
Dublin Rec	Lit	D297	Detritus	9/5/2019	-28.07	4.46
Dublin Rec	Lit	D447	Detritus	2/5/2020	-29.34	3.69
Dublin Rec	Lit	D448	Detritus	2/5/2020	-29.38	4.32
Dublin Rec	Lit	D449	Detritus	2/5/2020	-28.97	5.53
Dublin Rec	Lit	D555	Detritus	2/3/2021	-29.18	6.46
Dublin Rec	Lit	D556	Detritus	2/3/2021	-28.31	6.27
Dublin Rec	Lit	D557	Detritus	2/3/2021	-29.5	5.22
Dublin Rec	Lit	D615	Detritus	7/23/2020	-28.69	3.48
Dublin Rec	Lit	D616	Detritus	7/23/2020	-29.01	6.5
Dublin Rec	Lit	D617	Detritus	7/23/2020	-29.94	3.24
Dublin Rec	Unlit	D267	Detritus	9/5/2019	-28.61	6.06
Dublin Rec	Unlit	D278	Detritus	9/5/2019	-28.67	4.8
Dublin Rec	Unlit	D301	Detritus	9/5/2019	-27.66	6.85
Dublin Rec	Unlit	D442	Detritus	2/5/2020	-29.64	5.37
Dublin Rec	Unlit	D446	Detritus	2/5/2020	-29.85	3.09

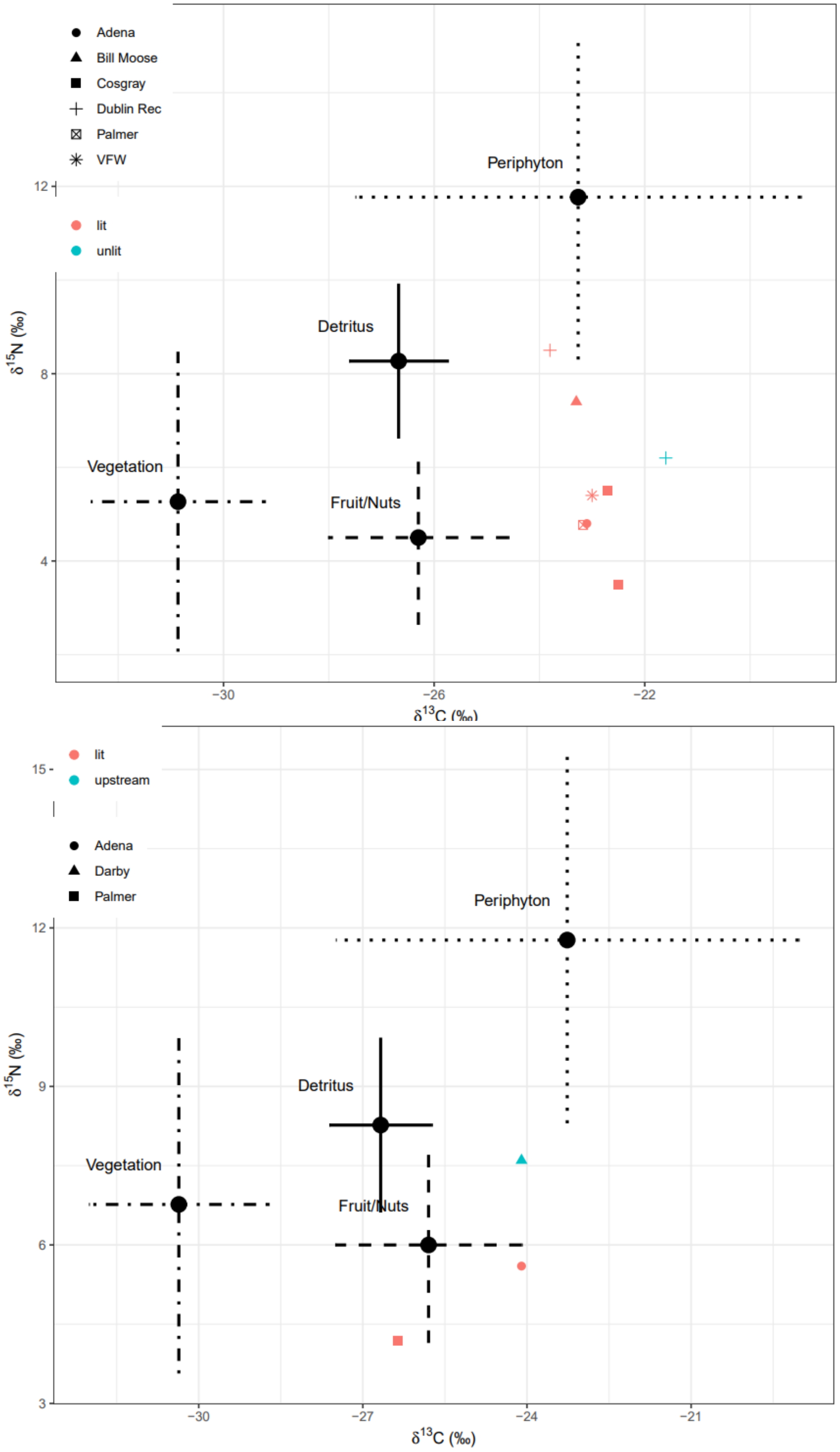
Dublin Rec	Unlit	D450	Detritus	2/5/2020	-30.02	2.98
Dublin Rec	Unlit	D558	Detritus	2/3/2021	-29.48	3.81
Dublin Rec	Unlit	D559	Detritus	2/3/2021	-26.26	0.31
Dublin Rec	Unlit	D560	Detritus	2/3/2021	-28.91	2.14
Dublin Rec	Unlit	D618	Detritus	7/23/2020	-28.01	3.97
Dublin Rec	Unlit	D619	Detritus	7/23/2020	-28.45	5.19
Dublin Rec	Unlit	D620	Detritus	7/23/2020	-27.98	4.32
Grove City	Lit	D266	Detritus	10/7/2019	-29.43	3.09
Grove City	Lit	D271	Detritus	10/7/2019	-27.44	2.11
Grove City	Lit	D307	Detritus	10/7/2019	-28.88	1.74
Grove City	Lit	D508	Detritus	3/11/2020	-28.61	4.04
Grove City	Lit	D509	Detritus	3/11/2020	-30.09	4.72
Grove City	Lit	D510	Detritus	3/11/2020	-28.97	3.98
Grove City	Lit	D561	Detritus	2/23/2021	-28.95	4.68
Grove City	Lit	D562	Detritus	2/23/2021	-29.37	3.63
Grove City	Lit	D563	Detritus	2/23/2021	-28.44	4.51
Grove City	Lit	D639	Detritus	7/28/2020	-28.23	2.83
Grove City	Lit	D640	Detritus	7/28/2020	-29.13	1.86
Grove City	Lit	D641	Detritus	7/28/2020	-28.15	4.95
Grove City	Unlit	D259	Detritus	10/7/2019	-29.25	5.94
Grove City	Unlit	D284	Detritus	10/7/2019	-27.99	1.42
Grove City	Unlit	D292	Detritus	10/7/2019	-30.55	2.85
Grove City	Unlit	D465	Detritus	3/11/2020	-29.38	3.97
Grove City	Unlit	D511	Detritus	3/11/2020	-28.54	5.07
Grove City	Unlit	D512	Detritus	3/11/2020	-29.12	4.39
Grove City	Unlit	D564	Detritus	2/23/2021	-27.2	1.87
Grove City	Unlit	D565	Detritus	2/23/2021	-29.55	2.64
Grove City	Unlit	D566	Detritus	2/23/2021	-29.1	5.81
Grove City	Unlit	D642	Detritus	7/28/2020	-29.06	4.57
Grove City	Unlit	D643	Detritus	7/28/2020	-27.15	5.36
Grove City	Unlit	D644	Detritus	7/28/2020	-28.51	4
Noble	Lit	D246	Detritus	9/19/2019	-28.16	-1.51
Noble	Lit	D256	Detritus	9/19/2019	-29.94	-0.48
Noble	Lit	D272	Detritus	9/19/2019	-28.73	0.63
Noble	Lit	D454	Detritus	1/7/2020	-28.71	3.04
Noble	Lit	D455	Detritus	1/7/2020	-28.99	1
Noble	Lit	D456	Detritus	1/7/2020	-27.98	2.25
Noble	Lit	D537	Detritus	1/21/2021	-27.85	2.19
Noble	Lit	D538	Detritus	1/21/2021	-28.77	3.49
Noble	Lit	D539	Detritus	1/21/2021	-28.17	2.45
Noble	Lit	D633	Detritus	7/27/2020	-29.84	-0.34
Noble	Lit	D634	Detritus	7/27/2020	-29.47	0.14
Noble	Lit	D635	Detritus	7/27/2020	-28.33	1.21
Noble	Unlit	D279	Detritus	9/19/2019	-28.86	-0.42

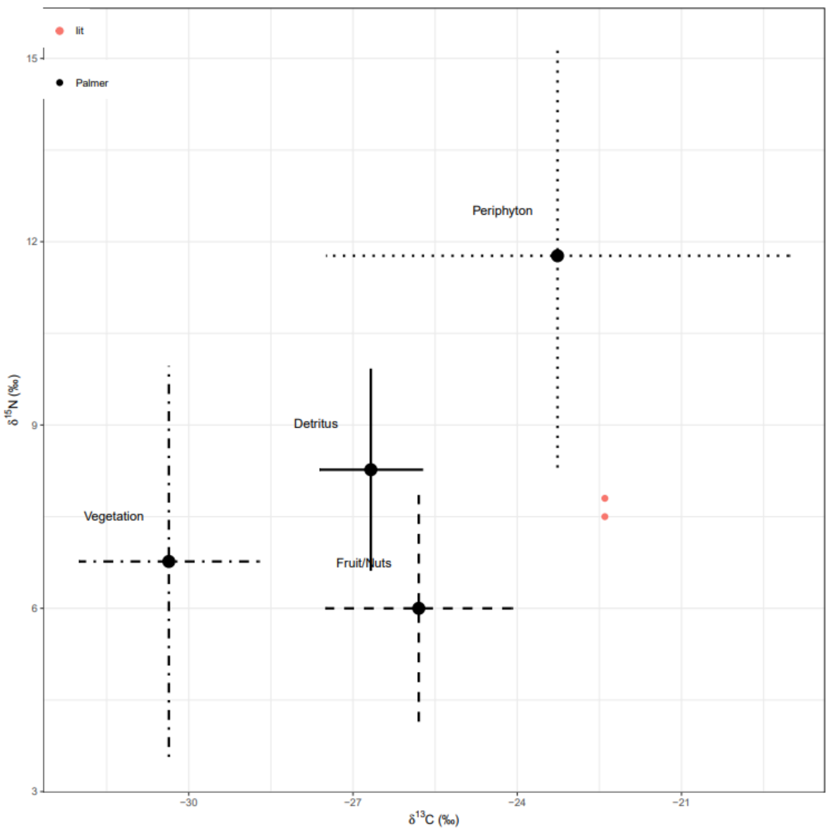
Noble	Unlit	D282	Detritus	9/19/2019	-29.76	-0.73
Noble	Unlit	D309	Detritus	9/19/2019	-28.7	3.09
Noble	Unlit	D457	Detritus	1/7/2020	-29.62	1.98
Noble	Unlit	D458	Detritus	1/7/2020	-28.25	3.42
Noble	Unlit	D459	Detritus	1/7/2020	-27.84	0.25
Noble	Unlit	D540	Detritus	1/21/2021	-28.35	3.13
Noble	Unlit	D541	Detritus	1/21/2021	-28.54	2.78
Noble	Unlit	D542	Detritus	1/21/2021	-27.94	2.57
Noble	Unlit	D636	Detritus	7/27/2020	-28.47	-0.13
Noble	Unlit	D637	Detritus	7/27/2020	-29.8	3.31
Noble	Unlit	D638	Detritus	7/27/2020	-29.24	0.89
Palmer	Lit	D273	Detritus	9/12/2019	-27.21	0.4
Palmer	Lit	D285	Detritus	9/12/2019	-28.55	2.31
Palmer	Lit	D300	Detritus	9/12/2019	-26.8	1.18
Palmer	Lit	D502	Detritus	3/9/2020	-29.21	1.24
Palmer	Lit	D503	Detritus	3/9/2020	-29.08	0.75
Palmer	Lit	D504	Detritus	3/9/2020	-29.49	1.57
Palmer	Lit	D513	Detritus	1/13/2021	-28.35	3.17
Palmer	Lit	D514	Detritus	1/13/2021	-28.31	2.61
Palmer	Lit	D515	Detritus	1/13/2021	-28.34	1.42
Palmer	Lit	D585	Detritus	7/6/2020	-27.53	0.64
Palmer	Lit	D586	Detritus	7/6/2020	-28.65	2.23
Palmer	Lit	D587	Detritus	7/6/2020	-27.68	2.64
Palmer	Unlit	D255	Detritus	9/12/2019	-27	1.92
Palmer	Unlit	D260	Detritus	9/12/2019	-29.48	0.16
Palmer	Unlit	D289	Detritus	9/12/2019	-28.32	3.09
Palmer	Unlit	D505	Detritus	3/9/2020	-28.73	1.09
Palmer	Unlit	D506	Detritus	3/9/2020	-29.32	2.34
Palmer	Unlit	D507	Detritus	3/9/2020	-29.49	2.49
Palmer	Unlit	D516	Detritus	1/13/2021	-28.65	3.05
Palmer	Unlit	D517	Detritus	1/13/2021	-26.35	3.86
Palmer	Unlit	D518	Detritus	1/13/2021	-29.76	2.9
Palmer	Unlit	D588	Detritus	7/6/2020	-27.77	0.43
Palmer	Unlit	D589	Detritus	7/6/2020	-25.56	2.61
Palmer	Unlit	D590	Detritus	7/6/2020	-25.99	-0.99
Redick	Downstream	D254	Detritus	9/10/2019	-28.32	1.72
Redick	Downstream	D287	Detritus	9/10/2019	-28.79	1.76
Redick	Downstream	D481	Detritus	2/11/2020	-29.3	1.55
Redick	Downstream	D482	Detritus	2/11/2020	-28.26	2.05
Redick	Downstream	D483	Detritus	2/11/2020	-29.39	1.89
Redick	Downstream	D570	Detritus	2/11/2021	-28.28	3.15
Redick	Downstream	D571	Detritus	2/11/2021	-28.31	3.87
Redick	Downstream	D572	Detritus	2/11/2021	-28.99	4.57
Redick	Downstream	D600	Detritus	7/14/2020	-30.32	3.69

Redick	Downstream	D601	Detritus	7/14/2020	-29.22	2.78
Redick	Downstream	D602	Detritus	7/14/2020	-26.66	5.85
Redick	Upstream	D250	Detritus	9/10/2019	-28.22	1.06
Redick	Upstream	D283	Detritus	9/10/2019	-27.16	2.19
Redick	Upstream	D315	Detritus	9/10/2019	-29.02	3.13
Redick	Upstream	D478	Detritus	2/11/2020	-28.05	2.97
Redick	Upstream	D479	Detritus	2/11/2020	-29.53	2.16
Redick	Upstream	D480	Detritus	2/11/2020	-28.61	1.58
Redick	Upstream	D567	Detritus	2/11/2021	-28.87	7.36
Redick	Upstream	D568	Detritus	2/11/2021	-29.53	3.08
Redick	Upstream	D569	Detritus	2/11/2021	-27.69	0.54
Redick	Upstream	D597	Detritus	7/14/2020	-26.5	1.11
Redick	Upstream	D598	Detritus	7/14/2020	-27.28	0.83
Redick	Upstream	D599	Detritus	7/14/2020	-29.04	-0.54
Rita's	Lit	D248	Detritus	9/16/2019	-28.45	1.5
Rita's	Lit	D251	Detritus	9/16/2019	-29.65	2.36
Rita's	Lit	D298	Detritus	9/16/2019	-29.67	2.42
Rita's	Lit	D484	Detritus	2/12/2020	-29.1	2.41
Rita's	Lit	D485	Detritus	2/12/2020	-28.88	1.09
Rita's	Lit	D486	Detritus	2/12/2020	-28.84	1.5
Rita's	Lit	D543	Detritus	1/26/2021	-29.54	2.42
Rita's	Lit	D544	Detritus	1/26/2021	-28.48	1.44
Rita's	Lit	D545	Detritus	1/26/2021	-27.43	3.45
Rita's	Lit	D645	Detritus	7/13/2020	-29.17	1.29
Rita's	Lit	D646	Detritus	7/13/2020	-27.29	2.07
Rita's	Lit	D647	Detritus	7/13/2020	-27.03	2.14
Rita's	Unlit	D302	Detritus	9/16/2019	-28.12	2.88
Rita's	Unlit	D311	Detritus	9/16/2019	-28.88	2.82
Rita's	Unlit	D312	Detritus	9/16/2019	-28.77	4.22
Rita's	Unlit	D487	Detritus	2/12/2020	-29.36	2.41
Rita's	Unlit	D488	Detritus	2/12/2020	-29.48	2.24
Rita's	Unlit	D489	Detritus	2/12/2020	-27.95	3.19
Rita's	Unlit	D546	Detritus	1/26/2021	-29.37	2.61
Rita's	Unlit	D547	Detritus	1/26/2021	-29.16	1.78
Rita's	Unlit	D548	Detritus	1/26/2021	-28.09	2.72
Rita's	Unlit	D648	Detritus	7/13/2020	-28.75	3
Rita's	Unlit	D649	Detritus	7/13/2020	-28.59	1.68
Rita's	Unlit	D650	Detritus	7/13/2020	-28.61	2.28
Sycamore	Lit	D257	Detritus	9/7/2019	-28.1	2.59
Sycamore	Lit	D277	Detritus	9/7/2019	-28.17	4.19
Sycamore	Lit	D290	Detritus	9/7/2019	-28.76	1.84
Sycamore	Lit	D466	Detritus	1/31/2020	-27.49	0.92
Sycamore	Lit	D467	Detritus	1/31/2020	-27.49	1.22
Sycamore	Lit	D468	Detritus	1/31/2020	-27.12	-0.19

Sycamore	Lit	D573	Detritus	2/26/2021	-25.67	1.02
Sycamore	Lit	D574	Detritus	2/26/2021	-27.29	1.49
Sycamore	Lit	D575	Detritus	2/26/2021	-27.81	-1.31
Sycamore	Lit	D591	Detritus	7/10/2020	-26.61	1.55
Sycamore	Lit	D592	Detritus	7/10/2020	-26.96	1.61
Sycamore	Lit	D593	Detritus	7/10/2020	-27.48	3.61
Sycamore	Unlit	D261	Detritus	9/7/2019	-29.7	2.98
Sycamore	Unlit	D275	Detritus	9/7/2019	-30.94	3.92
Sycamore	Unlit	D293	Detritus	9/7/2019	-29.02	1.99
Sycamore	Unlit	D469	Detritus	1/31/2020	-28.75	1.49
Sycamore	Unlit	D470	Detritus	1/31/2020	-29.41	1
Sycamore	Unlit	D471	Detritus	1/31/2020	-29.34	1.86
Sycamore	Unlit	D576	Detritus	2/26/2021	-29.43	1.5
Sycamore	Unlit	D577	Detritus	2/26/2021	-26.62	0.44
Sycamore	Unlit	D578	Detritus	2/26/2021	-28.68	0.65
Sycamore	Unlit	D594	Detritus	7/10/2020	-28.83	2.05
Sycamore	Unlit	D595	Detritus	7/10/2020	-29.11	1.31
Sycamore	Unlit	D596	Detritus	7/10/2020	-28.07	1.48
VFW	Lit	D281	Detritus	9/12/2019	-30.27	5.34
VFW	Lit	D294	Detritus	9/12/2019	-26.6	2.42
VFW	Lit	D303	Detritus	9/12/2019	-28.9	1.5
VFW	Lit	D490	Detritus	2/18/2020	-28.99	1.98
VFW	Lit	D491	Detritus	2/18/2020	-28.88	1.69
VFW	Lit	D492	Detritus	2/18/2020	-29.8	2.33
VFW	Lit	D519	Detritus	1/13/2021	-28.64	2.98
VFW	Lit	D520	Detritus	1/13/2021	-29.21	1.87
VFW	Lit	D521	Detritus	1/13/2021	-28.39	4.29
VFW	Lit	D603	Detritus	7/15/2020	-27.9	2.08
VFW	Lit	D604	Detritus	7/15/2020	-28.97	3.26
VFW	Lit	D605	Detritus	7/15/2020	-28.36	3.43
VFW	Unlit	D286	Detritus	9/12/2019	-29.47	0.69
VFW	Unlit	D288	Detritus	9/12/2019	-28.93	2.34
VFW	Unlit	D305	Detritus	9/12/2019	-29.37	3.61
VFW	Unlit	D493	Detritus	2/18/2020	-29.21	1.99
VFW	Unlit	D494	Detritus	2/18/2020	-29.35	1.45
VFW	Unlit	D495	Detritus	2/18/2020	-29.45	2.48
VFW	Unlit	D522	Detritus	1/13/2021	-28.73	1.7
VFW	Unlit	D523	Detritus	1/13/2021	-29.48	2.37
VFW	Unlit	D524	Detritus	1/13/2021	-28.39	2.35
VFW	Unlit	D606	Detritus	7/15/2020	-29.64	4.68
VFW	Unlit	D607	Detritus	7/15/2020	-26.65	3.6
VFW	Unlit	D608	Detritus	7/15/2020	-28.92	5.23

Appendix F: Isospace plots for *Tamias striatus* (top), *Blarina brevicauda* (middle), and *Didelphis virginiana* (bottom) separated by site and reach.




lit
Palmer
15
12
9
6
3
δ15N (‰)
Periphyton
Detritus
Vegetation
Fruit/Nuts
−30
−27
−24
−21
δ13C (‰)

Appendix G: Credible interval plots comparing basal resource energy contributions to *Peromyscus* between sites (a: Adena; b: Cosgray; c: Dublin Rec; d: Grove City; e: Palmer; f: Rita’s; g: Sycamore; h: VFW).