Bat Activity Correlates with Moth Abundance on an Urban Green Roof

Dustin R. Partridge[1,2,*], Kaitlyn L. Parkins[2], Susan B. Elbin[2], and J. Alan Clark[1]

Abstract - Global wildlife populations are in decline, in part, due to habitat loss resulting from urbanization. Urban green roofs may mitigate such habitat loss by providing supplemental habitat for wildlife, including bats, which are more active over urban green roofs than nearby traditional roofs. To better understand bat activity over urban green roofs, we surveyed bats and arthropods on a 27,316-m^2 green roof planted with *Sedum* spp. in New York City from June to August 2017. We found that *Lasiurus borealis* (Eastern Red Bat), a species with a diet consisting mainly of moths, accounted for 88% of identified bat calls. We collected over 15,000 arthropods of 16 taxa and found that moth abundance, while a relatively small proportion of green roof arthropods, correlated positively with bat activity. Our findings suggest that urban green roofs provide useable habitat for moths and other arthropods and, consequently, bats may forage on green roofs when prey are available.

Introduction

Global vertebrate (Pimm and Raven 2000) and invertebrate (Sánchez-Bayo and Wyckhuys 2019) populations are in decline, in part, due to habitat loss as a result of urbanization (McKinney 2008, Sánchez-Bayo and Wyckhuys 2019, Tilman et al. 2017). However, increasing green space in urban areas can help mitigate such habitat loss and provide conservation benefits (Gibb and Hochuli 2002, Oliver et al. 2011, Sandifer et al. 2015, Threlfall et al. 2015). Larger urban green spaces, such as parks, increase biodiversity (Chong et al. 2014, Vergnes et al. 2012), and connectivity between large green spaces allows for maintenance of urban wildlife populations (Braaker et al. 2017, Kang et al. 2015, Vergnes et al. 2012). Even relatively small urban green spaces, such as yards (Belaire et al. 2014, Lerman and Warren 2011) and green roofs (Eakin et al. 2015, Parkins and Clark 2015, Partridge and Clark 2018), can provide valuable conservation benefits.

The installation of green roofs, which are roofs covered with an impermeable membrane, growing medium, and vegetation (Oberndorfer et al. 2007), is one approach to increasing green space in urban areas. Green roofs provide multiple environmental and economic benefits. For example, green roofs aid stormwater management by reducing runoff quantity and pollutant load (Abualfaraj et al. 2018, Gregoire and Clausen 2011), reducing energy use for heating and cooling (Alvizuri et al. 2017), improving air quality (Speak et al. 2012), decreasing urban noise (Galbrun and Scerri 2017), and reducing urban heat-island effects (Santamouris 2014).

[1]Department of Biological Sciences, Fordham University, 441 East Fordham Road, Bronx, NY 10458. [2]New York City Audubon Society, 71 West 23rd St. New York, NY 10010. [*]Corresponding author - DPartridge@fordham.edu.

Manuscript Editor: Susan Herrick

Green roofs are usually designed with limited plant diversity but can nonetheless provide habitat for a diverse array of animal species (Eakin et al. 2015, MacIvor and Ksiazek 2015, Madre et al. 2013, Páll-Gergely et al. 2015, Parkins and Clark 2015, Partridge and Clark 2018). For example, urban green roofs are habitat for abundant and diverse arthropod communities (Joimel et al. 2018, Ksiazek-Mikenas et al. 2018, Partridge and Clark 2018, Starry et al. 2018) that are often similar in species composition to ground-level habitats (MacIvor and Lundholm 2011), though they are generally less diverse (Braaker et al. 2017, MacIvor and Lundholm 2011). Urban green roofs are also habitat for numerous bird species (Eakin et al. 2015, Partridge and Clark 2018, Washburn et al. 2016), especially insectivorous species, with more birds found on green roofs than nearby comparable conventional roofs (Partridge and Clark 2018). Insectivorous birds use green roofs more than conventional roofs during both migration and the breeding season, possibly foraging on arthropods there (Partridge and Clark 2018). Bats also use green roofs (Parkins and Clark 2015, Pearce and Walters 2012), and as with arthropods and birds, bats use green roofs more than nearby conventional roofs (Parkins and Clark 2015).

While arthropods, birds, and bats use urban green roofs as habitat, relationships between co-occurring species on green roofs are not frequently studied. For example, while bat activity is higher over green roofs than comparable conventional roofs, the ecological driver of this higher activity is not understood. Insectivorous predators, such as bats and birds, may be more active on green roofs due to the higher abundance of arthropods (Parkins and Clark 2015, Partridge and Clark 2018); however, this predicted relationship has not yet been demonstrated. Insectivorous bat species, such as *Lasiurus borealis* Müller (Eastern Red Bat), frequently prey on moths (Lepidoptera), and the abundance of moth-foraging bats can depend on local moth abundance (Dodd et al. 2008, Sierro and Arlettaz 1997, Wickramasinghe et al. 2004). Moth abundance, in turn, can predict bat activity (Wickramasinghe et al. 2004, Zeale et al. 2012). Consequently, preserving or introducing moth habitat benefits bat populations (Arrizabalaga-Escudero et al. 2015, Dodd et al. 2008, Wickramasinghe et al. 2004). Installation of urban green roofs can create new moth habitat (Partridge and Clark 2018) and thereby potentially create bat habitat.

Five species of bats have been regularly recorded in New York City: Eastern Red Bat, *L. cinereus* Palisot de Beauvois (Hoary Bat), *L. noctivagans* Le Conte (Silver-haired Bat), *Perimyotis subflavus* F. Cuvier (Tricolored Bat), and *Eptesicus fuscus* Palisot de Beauvois (Big Brown Bat) (Parkins et al. 2016). These same species use (i.e., vocalize over) New York City green roofs (Parkins and Clark 2015). In addition, a sixth species, *Myotis lucifugus* Le Conte (Little Brown Bat), has more recently been recorded in large parks in New York City (J.A. Clark, unpubl. data).The Eastern Red Bat is the most active species over New York City green roofs in the summer, accounting for up to 66% of bat vocalizations (Parkins and Clark 2015).

Bat species in New York City have similar diets, and all species are known to consume moths, Diptera (flies), Coleoptera (beetles), Orthoptera (crickets and grasshoppers), Hemiptera (true bugs), Hymenoptera (wasps and bees), Araneae (spiders), and Neuroptera (lacewings) (Arrizabalaga-Escudero et al. 2015, Barclay and

Coleman 2013, Cravens et al. 2018, Dixon 2012, Krüger et al. 2014) with some variation in percent composition of each species' diet. Moths, however, are an especially important food source for all New York City bat species (Clare et al. 2009, Cravens et al. 2018, Howard et al. 2012, Jesika et al. 2010), and moths are common on New York City green roofs (Partridge and Clark 2018). Thus, moths on urban green roofs have the potential to act as a food source for bats, particularly Eastern Red Bats, whose diet is largely composed of moths (Clare et al. 2009, Whitaker 1972), especially under nocturnal urban artificial light conditions (Cravens et al. 2018). Both bats and moths are found on green roofs, and, although the presence of moths could help explain the higher levels of bat activity on green roofs, no study to date has examined the relationship between moth abundance and bat activity on green roofs.

To better understand the relationship between bats and their arthropod prey on urban green roofs, we surveyed both bat and arthropod communities on a large *Sedum* green roof in New York City and compared overall bat activity with overall arthropod abundance. Because bats consume only a relatively small subset of arthropod species, we predicted that bat activity would not correlate with overall arthropod abundance; however, we predicted that bat activity would correlate positively with moth abundance. Because the Eastern Red Bat is the most common local bat species, we also examined how only Eastern Red Bat activity would correlate with both overall arthropod abundance as well as with moth abundance.

Field Site Description and Methods

Site

We surveyed the north side of the Jacob K. Javits Convention Center green roof (Javits green roof), located at 655 W. 34th Street, New York, NY (Fig. 1). The Javits green roof is located ~50 m from the Hudson River in a highly urbanized area with little surrounding green space, with the exception of trees planted in traffic medians along the West Side Highway and the High Line Park to the south. The 27,316-m^2 Javits green roof is extensive and planted with *Sedum* species (Fig. 1), plants that are relatively tolerant of the drier and windier conditions found on green roofs.

Bat acoustic surveys

To track bat activity, we installed a single Song Meter SM3BAT acoustic ultrasonic bat recorder (Wildlife Acoustics, Maynard, MA) near the center of the north side of the roof (Fig. 1) on 1 June 2017 and recorded nightly through 30 August 2017. The recorder was programmed to automatically record bat vocalizations (calls) throughout the night, from civil twilight to civil dawn. We set the recorders with a 192 kHz sample rate, 12 kHz digital high-pass filter, 18 dB trigger level, 36 db gain, and the mic bias off. We used a 2.0-sec trigger window minimum and an 8.0-sec maximum to create individual sound files of an appropriate length for the acoustic analysis software.

We analyzed sound files for all nights that coincided with the 48-hour arthropod sampling periods described below (Table 1). Sound files were passed through SonoBat Batch Scrubber Utility 5.2 (DND Design, Arcata, CA) using default settings to remove the majority of files that did not contain bat calls. We defined a bat call as a sound file with 2 or more pulses (Kalcounis et al. 1999, White and Gehrt 2001).

Figure 1. Satellite view of the Jacob K. Javits Convention Center green roof in New York City, NY. Bat activity and arthropod abundance was surveyed on the north side of the green roof (area within dashed line) from June through August 2017. * Indicates the location of the single Song Meter SM3BAT acoustic ultrasonic bat recorder.

Table 1. Arthropods collected on the Jacob K. Javits Convention Center green roof using bowl, sticky, and pitfall traps. Traps were deployed for 48-hour periods from June through August 2017. Units are individuals/trap. UID = unidentified taxa.

	Date							
Taxa	6/8	6/16	6/22	6/28	7/13	7/27	8/11	8/30
Acari	0.02	0.02	0.04	0.02	-	0.37	0.03	-
Coleoptera	0.06	0.16	0.05	0.19	0.27	0.95	0.21	0.78
Collembola	1.30	0.55	0.37	0.14	0.73	1.61	0.10	0.41
Diptera	4.55	2.59	4.25	4.88	9.42	5.12	6.59	6.63
Hemiptera	0.23	3.90	3.46	3.62	5.56	0.78	0.38	2.83
Hymenoptera	0.13	2.33	1.16	0.76	2.40	1.76	0.79	1.02
Lepidoptera	0.13	0.51	0.05	0.03	0.16	0.10	0.51	8.07
Orthoptera	-	0.02	-	-	0.02	-	0.05	0.10
Thysanoptera	0.70	4.14	4.35	3.55	5.11	5.73	4.26	3.44
Neuroptera	-	-	-	0.02	-	-	0.15	0.02
Araneae	0.15	0.12	0.05	0.10	0.67	0.34	0.31	0.05
Formicidae	0.02	0.14	0.05	0.05	0.00	0.10	0.21	0.07
Zygentoma	-	-	-	-	-	-	0.03	
UID	-	-	-	-	0.02	-	-	-
Phthiraptera	0.04	-	-	0.02	-	-	-	-

Due to high levels of regular, high-frequency ambient noise that is characteristic of urban settings, we then visually inspected sound files on a time-frequency sonogram to manually eliminate files missed by the acoustic software program that contained only non-bat noise. Sound files containing bat calls were then classified to the species level using Sonobat 3.1.1 NNE (DND Design, Arcata, CA); we classified bat calls that could not be identified to the species level as "unidentified". If ≥2 bat pulses were recorded at the same time in a file, the file was visually inspected, and both calls were counted. We did not determine if calls were feeding buzzes or search phase due to the difficulty distinguishing between the two in an urban setting and the likelihood of the recorder missing a feeding buzz (McCracken et al. 2008, Parkins and Clark 2015).

Arthropod sampling

To survey arthropod abundance, we used 4 trap types. We deployed bowl, pitfall, and sticky traps for 48-hour periods; these traps types are commonly used to sample a variety of both flying and crawling arthropods (Braaker et al. 2017, Eymann et al. 2010, Weseloh 1986), with the goal of collecting a general sample of the arthropod community on the green roof. We also deployed a Townes style malaise trap (MegaView Science®, Taiwan) from sunset to sunrise to sample arthropods on 3 occasions. Malaise traps are commonly used to sample night-flying arthropods, and our goal was to investigate their feasibility as a survey tool for future studies of arthropods on green roofs.

Bowl traps were plastic 355-ml bowls in a school-bus yellow color, 17.8 cm in diameter and 5.58 cm deep. We secured the bowl traps to the roof by inserting 3 bamboo stakes through the edge of the bowl into the substrate. Each bowl was then partially filled with a solution consisting of 300 ml of water, 4 ml of detergent (Colgate-Palmolive Company, New York, NY) to act as a surfactant, and 3 g of table salt (NaCl) to act as a preservative. Sticky traps were 2-sided, yellow sticky traps (Seabright Laboratories, Emeryville, CA) measuring 7.6 cm by 12.7 cm. We set sticky traps to stand horizontally with wire stakes ~2.5 cm above the vegetation at that sampling location. Pitfall traps were constructed of plastic drinking cups (Dixie® 148-ml, clear plastic). Each pitfall trap was buried in the substrate so that the surface of the cup was flush with the surface of the substrate. We filled pitfall traps with the same solution as the bowl traps. The Townes style malaise trap had black walls and a white roof with a single collector filled with 70% ethanol. We secured the malaise trap to the roof using ropes, stakes, and cinderblocks.

For the bowl, pitfall, and sticky traps, we randomly selected 30 sampling locations. One trap of each type was deployed at each sampling location. We conducted a total of eight 48-hour samples (Table 1): weekly 48-hour sampling from 1 June 1 through 15 July 2017 and bi-weekly sampling from 9 July to 30 August 2017. *Larus argentatus* Pontoppidan (Herring Gull) nesting on the roof destroyed many traps before samples could be retrieved. We noted all destroyed traps and recorded the total number of traps successfully collected after each sampling effort.

We deployed the malaise trap 3 times in August. Malaise traps cannot be deployed under windy conditions, especially on a green roof, and we avoided nights with precipitation forecasted. The malaise trap was deployed in the same location in the center of the north roof during each sampling effort.

At the end of the sampling period, we removed arthropods from the bowl, pitfall, and malaise traps and stored them in 70% ethanol until identification. Sticky traps were placed in labeled plastic bags and stored in a standard freezer. We identified hexapods, isopods, and spiders to order and all other arthropods to subclass or class using a stereoscopic microscope and *Borror and Delongs Introduction to the Study of Insects, 7th Edition* (Johnson and Triplehorn 2005).

Data analysis

Only data from nights with both arthropod sampling and bat surveys were included in our analyses (eight 48-hour sampling efforts over 16 nights; Table 1). We calculated arthropod abundance as the total number of arthropods collected during a sampling effort divided by the number of traps collected at the end of the sampling period for (1) all arthropods and (2) moths. We calculated bat activity, to the species level where possible, using the total number of bat calls for the 2 nights associated with the 48-hour arthropod samples. We used SPSS (Version 25, IBM) to calculate a Pearson correlation coefficient with alpha set at 0.05 to test for correlations between arthropod abundance and bat activity. Results are given ± SD.

Results

Bat acoustic aurveys

We recorded a total of 38 sound files over 16 recording nights: 35 were identified as bat calls, and 3 were false triggers due to background noise. We recorded 3 species: Eastern Red Bat, Big Brown Bat, and Silver-haired Bat. We identified 73% (25/35) of calls to species. Eastern Red Bats accounted for 63% (22/35) of all calls and 88% (22/24) of calls identified to species. The activity of all bat species varied from 0 calls/48 hours to 20 calls/48 hours, peaking on 30 August 2017 (Fig. 2).

Arthropod surveys

We collected 15,276 arthropods representing 16 taxa from bowl, pitfall, and sticky traps and an additional 290 arthropods representing 6 taxa from the malaise trap. The most abundant taxa collected from bowl, pitfall, and sticky traps were flies (10.26 ± 2.31 individuals/trap), Collembola (springtails; 3.88 ± 0.55 individuals/trap), Thysanoptera (thripes; 3.75 ± 1.88 individuals/trap), and true bugs (3.27 ± 1.91 individuals/trap); moths were less abundant (0.74 ± 2.63 individuals/trap) (Table 1).

The abundance of all arthropod taxa collected from bowl, pitfall, and sticky traps per sampling effort varied from 7.34 to 24.36 individuals/trap. Moth abundance varied from 0.03 to 8.07 individuals/trap (Fig. 2), accounted for just 2.80% of the arthropods collected over the sampling season, and varied from 0.03% to 34.40% of the arthropods collected in a single 48-hour sampling period.

Malaise traps collected only flying taxa that are typically bat prey (including moths, flies, beetles, crickets and grasshoppers, true bugs, wasps and bees, and lacewings). The number of arthropods collected increased each sampling effort, with 43 individuals collected on 2 August, 77 individuals collected on 11 August, and 177 individuals collected on 21 August (Table 2). Moths accounted for 14%, 34%, and 98% of the collections on the 2nd, 11th, and 21st of August, respectively.

Correlations

Overall bat activity, which included all bat species, was not correlated with arthropod abundance (r = 0.62, P = 0.102). Nor was bat activity correlated

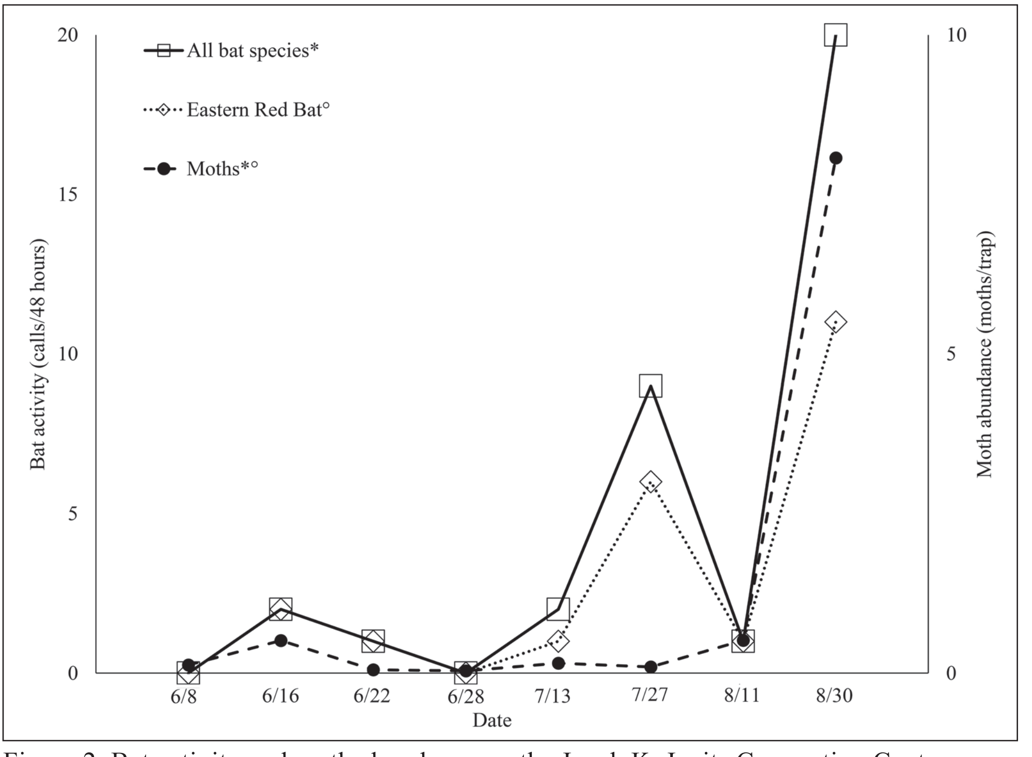

Figure 2. Bat activity and moth abundance on the Jacob K. Javits Convention Center green roof from June through August 2017. Moth abundance indicates the number of moths per trap collected in bowl, pitfall, and sticky traps over a 48-h sampling period. Bat activity indicates number of bat calls/48-h sampling period. All bats species included *Lasiurus borealis* (Eastern Red Bat), *L. noctivagans* (Silver-haired Bat), and *Eptesicus fuscus* (Big Brown Bat). Significant (P < 0.05) correlations (Pearson's correlation coefficient) are indicated by * and °.

Table 2. Arthropods collected on the Jacob K. Javits Convention Center green roof using a malaise trap. Arthropods were collected using a Townes style malaise trap on 3 nights in August 2017. The malaise trap was set at sunset and retrieved at sunrise. Numbers in parentheses are the percent composition of the total number of arthropods collected in given night.

Date	Coleoptera	Diptera	Hemiptera	Hymenoptera	Lepidoptera	Neuroptera	Total
8/2/2017	-	8 (18.60%)	14 (32.56%)	-	6 (13.95%)	15 (34.88%)	43
8/11/2017	1 (1.30%)	8 (10.39%)	34 (44.16%)	2 (2.60%)	26 (33.77%)	6 (7.76%)	77
8/21/2017	-	-	3 (1.76%)	-	166 (97.65%)	1 (0.59%)	170
Total	1 (0.34%)	19 (6.55%)	48 (16.55%)	2 (0.69%)	198 (68.28%)	22 (7.59%)	290

with arthropod abundance when considering only Eastern Red Bats (r = 0.59, P = 0.12). However, activity of bats overall and Eastern Red Bats did both correlate positively (r = 0.90, P = 0.002; r = 0.87, P = 0.006; respectively) when considering only moth abundance (Fig. 2).

Discussion

The arthropod community on the Javits green roof is diverse and abundant and, as with other green roofs, changes seasonally (Partridge and Clark 2018). Bats are also active on the Javits green roof, with species composition and nightly activity levels comparable to other green roofs in New York City (Parkins and Clark 2015).

As predicted, we found that bat activity on the Javits green roof correlated positively with moth abundance but not with overall arthropod abundance. While the conservation value of green roofs for bats is still not fully understood (Williams et al. 2014), we provide additional support for the prediction that bats are using urban green roofs for foraging (Parkins and Clark 2015), with bats calibrating their foraging activity on green roofs with the relative abundance of moths—their preferred prey.

We assessed bat use of green roofs by recording and calculating bat activity, which we measured as the number of bat calls recorded and not a count of the number of bats present at a site. Similar to other surveys conducted on green roofs in New York City (Parkins and Clark 2015), we used bat calls as a proxy for foraging activity, since foraging calls are difficult to record with the background noise found in urban environments (Fukui et al. 2006). Our comparison of bat activity to arthropod abundance demonstrates that, at least on the Javits green roof, bats use urban green roofs as foraging habitat when moth prey are present.

Bat activity correlating positively with moth abundance was likely driven by the high proportion of Eastern Red Bat calls in our sample (63% of all calls). The proportion of Eastern Red Bat calls on the Javits green roof is similar to other New York City green roofs, where Eastern Red Bats account for up to 66% of calls (Parkins and Clark 2015). Thus, we chose to also evaluate the data using only Eastern Red Bat activity. As noted earlier, Eastern Red Bats forage heavily on moths (Carter et al. 2004, Clare et al. 2009, Cravens et al. 2018), especially under conditions with artificial light (Cravens et al. 2018), such as in New York City. Bat species other than Eastern Red Bats that are foraging on the Javits green roof may forage more heavily on non-moth prey, but these bat species were too infrequent during our survey to fully assess their relationship with the arthropod community.

To look for other interactions between bats and potential prey beyond our initial predictions, we performed a post-hoc analysis testing for a correlation between bat activity and all known bat prey arthropods, other than moths (i.e., flies, beetles, crickets and grasshoppers, true bugs, wasps and bees, spiders, and lacewings). Using a Pearson correlation coefficient with alpha set at 0.05 we found that overall bat activity also correlated positively with beetle abundance (r = 0.76, P = 0.026) as well as cricket and grasshopper abundance (r = 0.76, P = 0.028), both orders which are active at night., both orders which are active at night. This finding may be a result of our small sample size, but it demonstrates the potential importance of other bat-prey arthropods for foraging bats on urban green roofs. The relationship between bat activity and other non-moth arthropods should be explored further.

Bat and moth activity changes seasonally, both due to life history (e.g., breeding, winter, and migration), but also possibly due to weather (Barclay and Coleman 2013, O'Donnell 2000, Wolbert et al. 2014). We expect the bat–moth dynamic we found during the summer to be different during spring, fall, and winter. In spring and fall, many bat species, including the Eastern Red Bat, migrate. As migratory bats pass through New York City, we would expect an increase in the numbers of bats (Parkins et al. 2016). This increase in bat activity, including Eastern Red Bat activity, could be due to the additional presence of arriving migrants. However, migrating bats have different physiology and foraging strategies than resident bats (Krüger et al. 2014, McGuire and Guglielmo 2009, McGuire et al. 2013, Parkins and Clark 2015), with migrating bats using different habitats than resident bats (Krüger et al. 2014). Little is known about how migratory bats use urban environments and green roofs, and the relationship between migrating bats and their prey on urban green roofs should also be investigated.

To further explore the relationships between urban bats and their prey, we recommend using focused night sampling for arthropods. Our experimental use of a malaise trap demonstrated the potential value of trapping methods that are more focused, resulting in the collection of flying taxa that are more likely to constitute bat prey than arthropods collected in bowl, sticky, and pitfall traps. Similar methods, such as light traps, have been used to examine bat prey availability in non-urban environments (e.g., Wolbert et al. 2014). However, since moths accustomed to long-term light pollution may be less responsive to light traps (Altermatt and Ebert 2016) and since urban green roofs are often illuminated by nearby buildings, unlit malaise traps may be more effective at sampling the nocturnal arthropod community.

Conclusion

To our knowledge, this study is the first examination of the relationship between insectivorous predators and their prey on an urban green roof. Our study examines a single site over the course of 1 season, but it demonstrates a potential interaction between predator and prey that has been proposed in previous studies of urban green roofs (Parkins and Clark 2015, Partridge and Clark 2018). Additional research is needed to more fully understand bat use of green roofs, but results from our study site indicate that arthropods on urban green roofs may attract bats, with moth-consuming bats using urban green roofs more when their preferred prey is available. Thus, information about arthropod community dynamics on green roofs can provide essential information about how we can design foraging habitat for bats in urban landscapes.

While green roofs should not be considered a substitute for ground-level habitats, they can provide additional habitat for wildlife in urban areas generally lacking green space. The benefits of green roofs are only beginning to be understood, and city planners, architects, building owners, and wildlife conservationists need to consider the role of green roofs when addressing the negative impacts of urbanization on wildlife.

Acknowledgments

This work was funded in part by the Jacob K. Javits Convention Center. We thank members of the Green Roof Researchers Alliance for their advice on this work, Robert Ciardullo for his help with fieldwork and arthropod identification, and Rick Brown for his field support, equipment fabrication, and availability. We also thank Rebecca Marshall, Tony Sclafani, and especially Alan Steel for access to the Javits Center and their openness to research.

Literature Cited

Abualfaraj, N., J. Cataldo, Y. Elborolosy, D. Fagan, S. Woerdeman, T. Carson, and F. Montalto. 2018. Monitoring and modeling the long-term rainfall-runoff response of the Jacob K. Javits Center green roof. Water 10:1494.

Altermatt, F., and D. Ebert. 2016. Reduced flight-to-light behaviour of moth populations exposed to long-term urban light pollution. Biology Letters 12:20160111.

Alvizuri, J., J. Cataldo, L.A. Smalls-Mantey, and F.A. Montalto. 2017. Green roof thermal buffering: Insights derived from fixed and portable monitoring equipment. Energy and Buildings 151:455–468.

Arrizabalaga-Escudero, A., I. Garin, J.L. García-Mudarra, A. Alberdi, J. Aihartza, and U. Goiti. 2015. Trophic requirements beyond foraging habitats: The importance of prey source habitats in bat conservation. Biological Conservation 191:512–519.

Barclay, R.M.R., and J.L. Coleman. 2013. Prey availability and foraging activity of grassland bats in relation to urbanization. Journal of Mammalogy 94:1111–1122.

Belaire, J.A., C.J. Whelan, and E.S. Minor. 2014. Having our yards and sharing them too: The collective effects of yards on native bird species in an urban landscape. Ecological Applications 24:2132–2143.

Braaker, S., M.K. Obrist, J. Ghazou, and M. Moretti. 2017. Habitat connectivity and local conditions shape taxonomic and functional diversity of arthropods on green roofs. Journal of Animal Ecology 86:521–531.

Carter, T.C., M.A. Menzel, B.R. Chapman, and K.V. Miller. 2004. Partitioning of food resources by syntopic Eastern Red (*Lasiurus borealis*), Seminole (*L. seminolus*), and Evening (*Nycticeius humeralis*) Bats. American Midland Naturalist 151:186–191.

Chong, K.Y., S. Teo, B. Kurukulasuriya, Y.F. Chung, S. Rajathurai, and H.T.W. Tan. 2014. Not all green is as good: Different effects of the natural and cultivated components of urban vegetation on bird and butterfly diversity. Biological Conservation 171:299–309.

Clare, E.L., E.E. Fraser, H.E. Braid, M.B. Fenton, and P.D. Hebert. 2009. Species on the menu of a generalist predator, the Eastern Red Bat (*Lasiurus borealis*): Using a molecular approach to detect arthropod prey. Molecular Ecology 18:2532–2542.

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

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

Dodd, L.E., M.J. Lacki, and L.K. Rieske. 2008. Variation in moth occurrence and implications for foraging habitat of Ozark Big-eared Bats. Forest Ecology and Management 255:3866–3872.

Eakin, C.J., H. Campa, D.W. Linden, G.J. Roloff, D.B. Rowe, and J. Westphal. 2015. Avian response to green roofs in urban landscapes in the midwestern USA. Wildlife Society Bulletin 39:574–582.

Eymann, J., J. Degreef, C. Häuser, J. Monje, Y. Samyn, and D. Vandenspiegel. 2010. Manual on Field Recording Techniques and Protocols for All Taxa Biodiversity Inventories and Monitoring. Belgian Development Cooperation, Brussels, Belgium. 653 pp.

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

Galbrun, L., and L. Scerri. 2017. Sound insulation of lightweight extensive green roofs. Building and Environment 116:130–139.

Gibb, H., and D.F. Hochuli. 2002. Habitat fragmentation in an urban environment: Large and small fragments support different arthropod assemblages. Biological Conservation 106:91–100.

Gregoire, B.G., and J.C. Clausen. 2011. Effect of a modular extensive green roof on stormwater runoff and water quality. Ecological Engineering 37:963–969.

Howard, T.H., P.R. Moosman, J.P. Veilleux, and J. Holt. 2012. Foods of bats (Family Vespertilionidae) at five locations in New Hampshire, and Massachusetts. The Canadian Field-Naturalist 126:117–124.

Jesika, R.P., B. Erin, and M.R. Robert. 2010. Diet of Hoary (*Lasiurus cinereus*) and Silver-haired (*Lasionycteris noctivagans*) Bats while migrating through southwestern Alberta in late summer and autumn. American Midland Naturalist 164:230–237.

Johnson, N.F., and C.A. Triplehorn. 2005. Borror and Delongs Introduction to the Study of Insects, 7th Edition. Cengage Learning, Independence, KY. 888 pp.

Joimel, S., B. Grard, A. Auclerc, M. Hedde, N. Le Doaré, S. Salmon, and C. Chenu. 2018. Are Collembola “flying” onto green roofs? Ecological Engineering 111:117–124.

Kalcounis, M., K. Hobson, R. Brigham, and K. Hecker. 1999. Bat activity in the boreal forest: Importance of stand type and vertical strata. Journal of Mammalogy 80:673–682.

Kang, W., E.S. Minor, C.R. Park, and D. Lee. 2015. Effects of habitat structure, human disturbance, and habitat connectivity on urban forest bird communities. Urban Ecosystems 18:857–870.

Krüger, F., E.L. Clare, W.O. Symondson, O. Keišs, and G. Pētersons. 2014. Diet of the insectivorous bat *Pipistrellus nathusii* during autumn migration and summer residence. Molecular Ecology 23:3672–3683.

Ksiazek-Mikenas, K., J. Herrmann, S.B. Menke, and M. Köhler. 2018. If you build it, will they come? Plant and arthropod diversity on urban green roofs over time. Urban Naturalist Special Issue 1:52–72.

Lerman, S.B., and P.S. Warren. 2011. The conservation value of residential yards: Linking birds and people. Ecological Applications 21:1327–1339.

MacIvor, J.S., and K. Ksiazek. 2015. Invertebrates on green roofs. Pp. 333–355, In R. Sutton (Ed.). Green Roof Ecosystems. Springer International Publishing, Cham, Switzerland. 447 pp.

MacIvor, J.S., and J. Lundholm. 2011. Insect species composition and diversity on intensive green roofs and adjacent level-ground habitats. Urban Ecosystems 14:225–241.

Madre, F., A. Vergnes, N. Machon, and P. Clergeau. 2013. A comparison of 3 types of green roof as habitats for arthropods. Ecological Engineering 57:109–117.

McCracken, G.F., E.H. Gillam, J.K. Westbrook, Y.-F. Lee, M.L. Jensen, and B.B. Balsley. 2008. Brazilian Free-tailed Bats (*Tadarida brasiliensis*: Molossidae, Chiroptera) at high altitude: Links to migratory insect populations. Integrative and Comparative Biology 48:107–118.

McGuire, L.P., and C.G. Guglielmo. 2009. What can birds tell us about the migration physiology of bats? Journal of Mammalogy 90:1290–1297.

McGuire, L.P., M.B. Fenton, and C.G. Guglielmo. 2013. Phenotypic flexibility in migrating bats: Seasonal variation in body composition, organ sizes, and fatty-acid profiles. Journal of Experimental Biology 216:800–808.

McKinney, M. 2008. Effects of urbanization on species richness: A review of plants and animals. Urban Ecosystems 11:161–176.

O'Donnell, C.F. 2000. Influence of season, habitat, temperature, and invertebrate availability on nocturnal activity of the New Zealand Long-tailed Bat (*Chalinolobus tuberculatus*). New Zealand Journal of Zoology 27:207–221.

Oberndorfer, E., J. Lundholm, B. Bass, R.R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Köhler, K.K. Liu, and B. Rowe. 2007. Green roofs as urban ecosystems: Ecological structures, functions, and services. BioScience 57:823–833.

Oliver, A.J., C. Hong-Wa, J. Devonshire, K.R. Olea, G.F. Rivas, and M.K. Gahl. 2011. Avifauna richness enhanced in large, isolated urban parks. Landscape and Urban Planning 102:215–225.

Páll-Gergely, B., K. Kyrö, S. Lehvävirta, and F. Vilisics. 2015. Green roofs provide habitat for the rare snail (Mollusca, Gastropoda) species *Pseudotrichia rubiginosa* and *Succinella oblonga* in Finland. Memoranda Societatis pro Fauna et Flora Fennica 90:13–15.

Parkins, K.L., and J.A. Clark. 2015. Green roofs provide habitat for urban bats. Global Ecology and Conservation 4:349–357.

Parkins, K.L., M. Mathios, C. McCann, and J.A. Clark. 2016. Bats in the Bronx: Acoustic monitoring of bats in New York City. Urban Naturalist 10:1–16.

Partridge, D.R., and J.A. Clark. 2018. Urban green roofs provide habitat for migrating and breeding birds and their arthropod prey. PLOS ONE 13:e0202298.

Pearce, H., and C.L. Walters. 2012. Do green roofs provide habitat for bats in urban areas? Acta Chiropterologica 14:469–478.

Pimm, S.L., and P. Raven. 2000. Biodiversity: Extinction by numbers. Nature 403:843.

Sánchez-Bayo, F., and K.A. Wyckhuys. 2019. Worldwide decline of the entomofauna: A review of its drivers. Biological Conservation 232:8–27.

Sandifer, P.A., A.E. Sutton-Grier, and B.P. Ward. 2015. Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: Opportunities to enhance health and biodiversity conservation. Ecosystem Services 12:1–15.

Santamouris, M. 2014. Cooling the cities: A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy 103:682–703.

Sierro, A., and R. Arlettaz. 1997. Barbastelle Bats (*Barbastella* spp.) specialize in the predation of moths: Implications for foraging tactics and conservation. Acta Oecologica 18:91–106.

Speak, A., J. Rothwell, S. Lindley, and C. Smith. 2012. Urban particulate pollution reduction by four species of green roof vegetation in a UK city. Atmospheric Environment 61:283–293.

Starry, O., S. Gonsalves, K. Ksiazek-Mikenas, J.S. MacIvor, M. Gardner, A. Szallies, and S. Brenneisen. 2018. A global comparison of beetle community composition on green roofs and the potential for homogenization. Urban Naturalist Special Issue 1:1–15.

Threlfall, C.G., K. Walker, N.S. Williams, A.K. Hahs, L. Mata, N. Stork, and S.J. Livesley. 2015. The conservation value of urban green space habitats for Australian native bee communities. Biological Conservation 187:240–248.

Tilman, D., M. Clark, D.R. Williams, K. Kimmel, S. Polasky, and C. Packer. 2017. Future threats to biodiversity and pathways to their prevention. Nature 546:73–81.

Vergnes, A., I.L. Viol, and P. Clergeau. 2012. Green corridors in urban landscapes affect the arthropod communities of domestic gardens. Biological Conservation 145:171–178.

Washburn, B.E., R.M. Swearingin, C.K. Pullins, and M.E. Rice. 2016. Composition and diversity of avian communities using a new urban habitat: Green roofs. Environmental Management 57:1230–1239.

Weseloh, R.M. 1986. Host and microhabitat preferences of forest parasitic Hymenoptera: Inferences from captures on colored sticky panels. Environmental Entomology 15:64–70.

Whitaker, J.O., Jr. 1972. Food habits of bats from Indiana. Canadian Journal of Zoology 50:877–883.

White, E.P., and S.D. Gehrt. 2001. Effects of recording media on echolocation data from broadband bat detectors. Wildlife Society Bulletin 29:974–978.

Wickramasinghe, L.P., S. Harris, G. Jones, and N. Vaughan Jennings. 2004. Abundance and species richness of nocturnal insects on organic and conventional farms: Effects of agricultural intensification on bat foraging. Conservation Biology 18:1283–1292.

Williams, N.S., J. Lundholm, and J.S. MacIvor. 2014. Do green roofs help urban biodiversity conservation? Journal of Applied Ecology 51:1643–1649.

Wolbert, S.J., A.S. Zellner, and H.P. Whidden. 2014. Bat activity, insect biomass, and temperature along an elevational gradient. Northeastern Naturalist 21:72–86.

Zeale, M.R., I. Davidson-Watts, and G. Jones. 2012. Home-range use and habitat selection by Barbastelle Bats (*Barbastella barbastellus*): Implications for conservation. Journal of Mammalogy 93:1110–1118.