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Insect pollinator and natural enemy communities in green roof and ground-level urban habitats

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Abstract
Urban greenspaces, including green roofs and ground-level urban habitats provide habitat for insect communities in cities. However, beneficial insect communities likely differ between human-managed habitats because of varying provision of resources and connectivity in these greenspaces. This study examined the insect communities in four extensive green roofs and three non-adjacent, similarly structured, managed ground-level habitats. We detected a high degree of overlap in insect taxa but found moderate differences in overall insect community composition between the green roof and ground-level habitats. While there was no difference in Shannon diversity between green roofs and ground-level habitats, the ground-level habitat had greater insect taxa richness. Green roof and ground-level habitats supported pollinators and natural enemies, while ground-level had greater mean pollinator and natural enemy richness and Shannon diversity. Green roofs intentionally designed for biodiversity using native plants for habitat did not differ from those designed for stormwater management and energy reduction using non-native plants in insect community metrics used in this study. These findings suggest that urban greenspaces continue to provide valuable habitat while connectivity and structure play a role in shaping urban insect communities.

Keywords Insects · Green roof · Managed habitats · Beneficial

Introduction

Human-managed and occupied urban green spaces may mimic the ecosystem functionality of naturally occurring habitats, either spontaneously or by design (Lundholm 2006; Oberndorfer et al. 2007). Understanding how communities of organisms assemble and use these novel spaces provides a key opportunity to understand, and potentially shape, the ecosystem functions and services delivered in human-dominated landscapes (Groffman et al. 2017; Mallinger et al. 2016). The structural elements that make a habitat unique is termed "habitat template" (Southwood 1977). The habitat template shapes which organisms can colonize by filtering out many species that are not suited for that habitat (Lundholm 2006). Using this theory, Lundholm (2006) developed the habitat template approach to urban biodesign, in which built elements, such as extensive green roofs, can be designed using elements from various ground-level thin-soil rock barren environments, due to the similar physical attributes they share. It has been suggested that a structural diversity of plants and abiotic factors in green roofs influences insect diversity (Brenneisen 2003).

Green roofs may, or may not, be designed to mimic similarly structured habitats in their region. The services that green roofs provide, including stormwater management, reduced energy consumption, accessible or visible green space, and habitat for organisms, among others, vary according to how the green roof is designed and maintained (Dunnett and Kingsbury 2004). As part of the urban built environment, green roofs may experience high wind and solar radiation, as well as periods of flooding or drought brought on by the thin substrate on top of a hard surface. These conditions limit primary producers' survival (Lundholm 2006). Thin soil (substrate) roofs are known

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as extensive green roofs, in which plants are intentionally grown on top of a human-built structure in shallow (typically 15–20 cm or less) growing medium (Getter and Rowe 2006; Oberndorfer et al. 2007). As opposed to intensive green roofs, which have at least 15 cm of substrate and may host a wide range of vegetation types, extensive roofs put less stress on buildings and can be less expensive (Dunnett and Kingsbury 2004). This intensive/extensive nomenclature has been used for some time to characterize green roofs (Dunnett and Kingsbury 2004; Getter and Rowe 2006; Oberndorfer et al. 2007; Razzaghmanesh and Beecham 2014; Starry et al. 2018; Stella and Personne 2021), but some authors also classify green roofs by their plant community or function (Kotze et al. 2020).

In many locations, roofs designed without specific biodiversity goals in mind commonly use exotic *Sedum* (*Phedimus*) species because as succulents they have been shown to withstand the challenging growing conditions, especially drought, on roofs (Dunnett and Kingsbury 2004; VanWoert et al. 2005). These *Sedum* based roofs initially became widely used in western Europe, especially Germany (Köhler 2006; Ngan 2004; Oberndorfer et al. 2007; Thuring and Grant 2015), and are now popular in many places of the world including North America (Dunnett and Kingsbury 2004; Dvorak and Volder 2010; Snodgrass and McIntyre 2010). When biodiversity service provision is a priority, designers may choose to use plants native to their region, creating a habitat analog. For example, prairie ecosystems are widely distributed in North America and commonly experience drought conditions, so these plants are well accustomed to the challenges often encountered on green roofs (Sutton et al. 2012). Although prairie plants, especially in tallgrass prairies, often have deep root systems (Nippert et al. 2012) many species root less deeply or will adapt to shallow growing mediums by growing roots horizontally (Sutton et al. 2012). The diversity of plant taxa found in prairies is also beneficial to their success as the richness supports ecosystem functioning (Cardinale et al. 2011; Tilman et al. 1996). Prairie analog roofs can be found in the Great Lakes Region of the United States of America (Dvorak 2015; Hawke 2015). Other ground-level thin-soil ecosystems that are structurally analogous to extensive green roofs, such as alvars, cliff edges, and barrens are found in the Great Lakes Basin (McNamara Manning et al. 2023). These natural environments experience similar environmental conditions to green roofs and have thin soils on top of bedrock, usually sandstone, limestone, or dolostone (Lundholm 2006). Studies examining plant performance on green roofs predominately seek suggestions for plant mixes suited to particular climates or for different design goals (Butler and Orians 2011; Cáceres et al. 2018, 2022; Calviño et al. 2023; Chell et al. 2022; Coffman and Blackson 2020; Farrell et al. 2022; Hawke 2015; Heim and Lundholm 2014; Köhler 2006; MacIvor and Lundholm 2011a; Monterusso et al. 2005; Nagase et al. 2017; Nagase and Dunnett 2010; among others).

Insects inhabit practically all terrestrial and freshwater ecosystems, including urban environments, and play a variety of critical roles in ecosystem function and service (Rosenberg et al. 1986), making them the ideal 'barometers' to measure biodiversity functions of green roofs. Insects that provide services such as pollination, pest control, and decomposition are commonly referred to as beneficial insects, and these groups provide billions of dollars' worth of ecosystem services to agricultural ecosystems in the United States each year (Losey and Vaughan 2006). Numerous studies have reported a wide variety of invertebrate taxa occurring in green roof habitats: beetles (Brenneisen 2003; Pétremand et al. 2018; Starry et al. 2018), bees (Colla et al. 2009; Kratschmer et al. 2018; Ksiazek et al. 2012; MacIvor et al. 2015; Tonietto et al. 2011) and other pollinators (Jacobs et al. 2023; MacIvor 2016; Passaseo et al. 2020, 2021), parasitoid wasps (Diethelm and Masta 2022), and a variety of mixed taxa (Coffman and Davis 2005; Coffman and Waite 2011; Fabián et al. 2021; Kadas 2006; Kyrö et al. 2020; MacIvor and Lundholm 2011b; Sánchez Domínguez et al. 2020). Green roofs designed with insect biodiversity and native resources in mind can provide habitat in these urban landscapes that have lost some of this space on the ground level (Brenneisen 2003, 2006; Lundholm 2006). However, green roofs not necessarily designed for biodiversity still provide habitat or foraging resources (Coffman and Davis 2005; Coffman and Waite 2011; MacIvor et al. 2015). In general, green spaces in human dominated landscapes can be important to support biodiversity and conservation (Tonietto et al. 2011), but the connectivity of these habitats may influence insect communities (Barr et al. 2021; Braaker et al. 2014, 2017).

To understand insect community composition several previous authors have compared green roofs and ground-level sites, often finding higher biodiversity at ground-level sites, but concluding that green roofs provided important habitat (Braaker et al. 2017; Colla et al. 2009; Ksiazek et al. 2012; MacIvor and Lundholm 2011a; Tonietto et al. 2011). However, less is known about ground-level habitats under management or protection, except Tonietto et al. (2011) examined managed prairies, city parks, and green roofs. They found a higher abundance and diversity of bees in prairies, compared to green roofs, with bee communities in city parks similar to both other habitats. There are conflicting conclusions when comparing insect communities on green roofs with different plant types. Kyrö et al. (2020) found differences between meadow and succulent roof insect communities in Finland, while Jacobs et al. (2023)

found no difference between *Sedum* and mixed vegetation roofs in Belgium.

Regarding beneficial insects, pollinator studies on green roofs are more abundant (Colla et al. 2009; Jacobs et al. 2023; Ksiazek et al. 2012; MacIvor et al. 2015; Passaseo et al. 2020, 2021; Tonietto et al. 2011) than studies examining natural enemies (Diethelm and Masta 2022; Fabián et al. 2021; Sánchez Domínguez et al. 2020). The majority of green roof insect studies use only one sampling method (Brenneisen 2003; Coffman and Davis 2005; Coffman and Waite 2011; Colla et al. 2009; Fabián et al. 2021; Kratschmer et al. 2018; Ksiazek et al. 2012; Kyrö et al. 2020; MacIvor and Lundholm 2011a; Passaseo et al. 2020, 2021; Sánchez Domínguez et al. 2020; Starry et al. 2018), but using multiple sampling methods can improve understanding of the insect community (Aguiar and Santos 2010; Campbell et al. 2023; McNamara Manning et al. 2022; Missa et al. 2009; Russo et al. 2011).

In this study, we aim to expand from current understandings by examining insect communities in green roofs and protected ground-level thin soil habitats using a multidimensional sampling approach to characterize the full community while on beneficial insects, including pollinators and natural enemies. Because urban infrastructure is designed and planned with different purposes, we compared the insect communities on green roofs designed with and without biodiversity in mind. We ask (1) how does insect community richness and Shannon diversity differ between ground-level and green roof habitats?; (2) how does insect community richness and Shannon diversity differ between green roofs designed for biodiversity and those designed for stormwater management and energy reduction? (3) how do beneficial insects, pollinators and natural enemies, differ between these habitats and green roof types? While green roofs and ground-level thin soil habitats may share common structuring characteristics, due to perceived greater connectivity with other habitats as well as findings from previous studies, we predict that total insect and beneficial insect richness and diversity will be greater in ground-level than green roof habitats. Between green roofs, we predict that total insect and beneficial insect richness and diversity will be greater among green roofs designed for biodiversity services versus those designed for other services like stormwater management and reducing energy consumption of the building.

Methods

Study sites

Seven locations, four green roof and three ground-level sites in the greater Cleveland, Ohio, USA area were sampled in 2019 and 2021 (Fig. 1). The structural and vegetative characteristics of all sites differed, but they had soils or substrates of similar depths, were open to solar radiation, winds, and precipitation. All sites were embedded in a greater landscape of mixed use, urban, semi-urban, and industrial land use histories, and had differing adjacencies. To assess greenspace surrounding each site, a GIS layer of Open Space was downloaded from Cuyahoga County Open Data, created by the Cuyahoga County Planning Commission Greenprint Service. Areas with primary land use designation listed as agriculture, preserved, recreation/recreational, conservation, park, or greenspace were selected and used as a greenspace layer. A 1.5 km buffer (Gardiner et al. 2009) was created around all study site points and percent greenspace within each buffer was calculated using the Tabulate Intersection tool in ArcGIS Pro (version 3.1.2).

The three ground-level sites were managed habitats located in conservation-based park systems each with a history of disturbance. The Slate Shale Hill was a roadside hill of highly exposed slate shale soil, surrounded by forest (Fig. 2a). Sparse vegetation and trees included mixed patches of *Danthonia spicata* (L.) Roem. & Schult. (Poverty Oat Grass), *Schizachyrium scoparium* (Michx.) Nash (Little Bluestem), several species of *Aster*, *Acer rubrum* L. (Red Maple), *Pinus strobus* L. (White Pine), and *Nyssa sylvatica* Marshall (Black Gum). The Dusty Goldenrod Meadow was a portion of a preserve that was an open wet meadow surrounded by forest and residential development (Fig. 2b). This site had continuous grass and sedge vegetation and sparse trees, including *Rhynchospora* sp. (Beaksedge), *Schizachyrium scoparium* (Little Bluestem), *Polygala nuttallii* Torr. & A.Gray (Nutall's Milkwort), *Acer rubrum* (Red Maple), *Pinus strobus* (White Pine), and *Nyssa slyvatica* (Black Gum). It is the only known home in Ohio to its namesake, the rare and endangered Dusty Goldenrod (*Solidago puberula* Nutt.). Bedford Barren was a thin-soil mossy barren adjacent to a hiking trail, between a meadow and forest, at a cliff edge over a creek (Fig. 2c). The site was located in a utility easement that is heavy machine brush-cut every 5–10 years. The barren mostly contained mosses, leaves, coarse woody debris, and *Danthonia spicata* (Poverty Oat Grass). In the adjacent meadow grew *Achillea millefolium* L. (Common Yarrow), several species of *Solidago* (Goldenrod), and *Daucus carota* L. (Queen Anne's Lace), and the adjacent trees were mostly *Acer rubrum* (Red Maple) and *Quercus rubra* L. (Northern Red Oak).

Among the four green roof sites, we sampled two green roof design types. Stormwater-energy (SE) green roofs were designed for stormwater management and to reduce building energy needs. Biodiversity-ecological (BE) green roofs were designed with ecomimicry and native plants in mind, utilizing greater plant diversity and providing habitat for

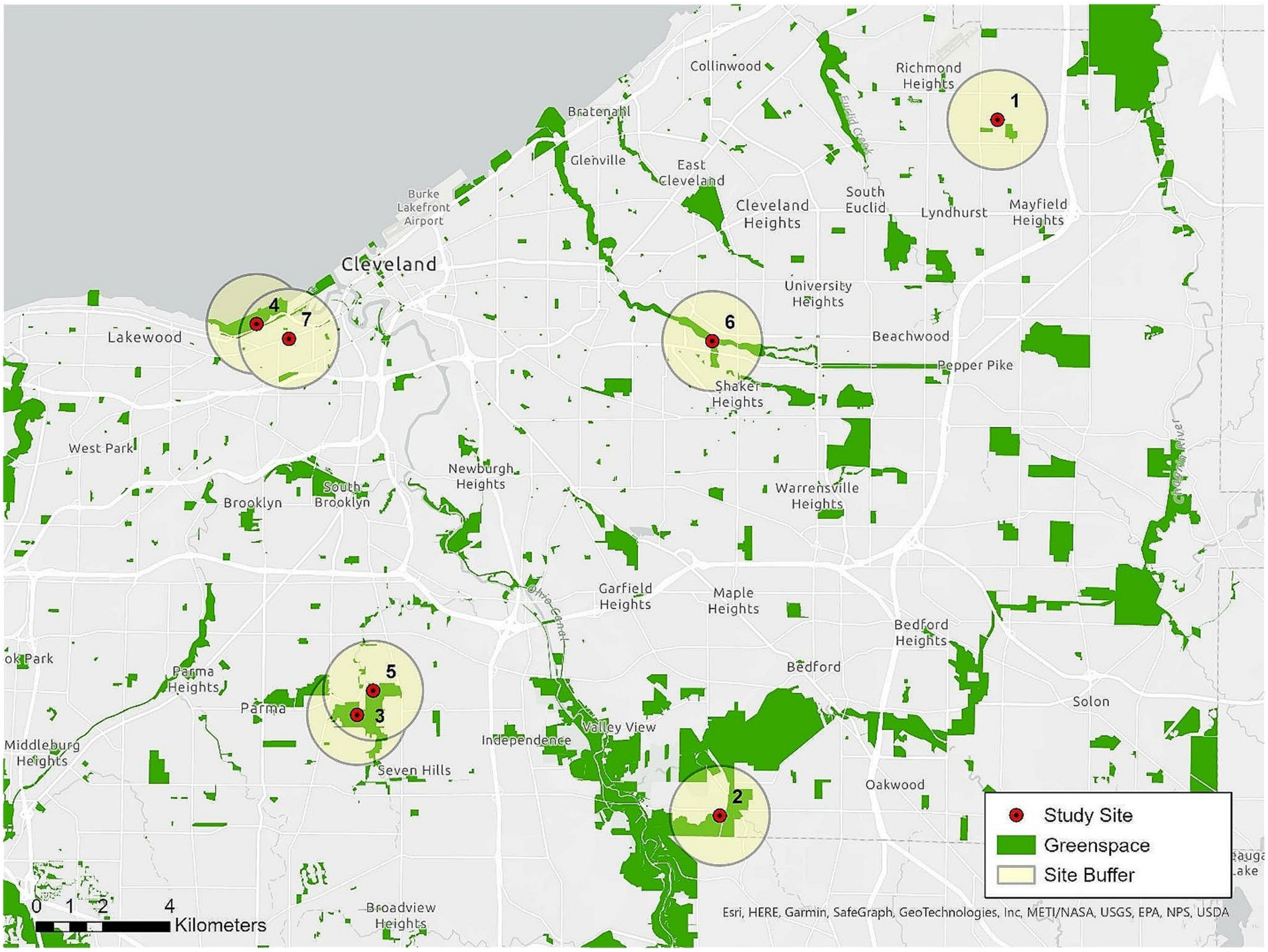

Fig. 1 Map of Cuyahoga County, Ohio displaying sampling sites with 1.5 km radii: Dusty goldenrod meadow (1), Bedford barren (2), Slate shale hill (3), Edgewater beach (4), Watershed Steward Center (5), Nature Center at Shaker Lakes (6), Happy Dog bike box (7). Map created by Stephanie Burkey using ArcGIS Pro.

wildlife (Droz et al. 2022; Kotze et al. 2020). The Edgewater Beach House roof (SE) at was designed to prevent stormwater runoff and cool the structure (Fig. 2e). The flat two-story roof, adjacent to Lake Erie, was planted with non-native *Sedum* and other low growing succulent species in a flexible modular system, including *Sedum sexangulare* L. (Tasteless Stonecrop), *Sedum acre* L. (Goldmoss Stonecrop), *Sedum montanum ssp. orientale* (Unusual Evergreen Sedum), *Sedum album* L. (White Stonecrop), *Phedimus spurius* (M. Bieb.) ‘t Hart (Two-row Stonecrop). The Watershed Stewardship Center roof (SE) was also designed for stormwater and energy benefits (Fig. 2f). Using a similar rigid modular system, the two-story sloped roof was planted with *Hylotelephium spectabile* ‘meteor’ (Showy Stonecrop), *Hylotelephium ewersii* (Pink Mongolian Stonecrop), *Sedum album brevifolium* (White Stonecrop), and *Allium senescens ssp. glaucum* (German Garlic). *Trifolium repens* L. (White Clover) has volunteered and is periodically weeded out but was present for our sampling. It was surrounded by native landscaping on the ground level and adjacent woods and streams. The Happy Dog Bike Box (BE) was built on a bike shelter and designed to mimic a prairie ecosystem (Fig. 2g). The one-story flat roof had a loose-laid system planted with *Bouteloua gracilis* (Kunth) Griffiths (Blue Gramma), *Solidago nemoralis* Aiton (Gray Goldenrod), *Solidago ptarmicoides* (Torrey & A. Gray) B. Boivin (White Flat-top Goldenrod), *Sporobolus heterolepis* A.Gray (Prairie Dropseed), *Symphyotrichum oblongifolium* (Nutt.) G.L. Nesom (Aromatic Aster), and *Viola pedatifida* G. Don (Prairie Violet). Notably, the structure had limited green space at the ground level surrounding it. This roof was considered semi-intensive because although most of it has thin soil, it also utilized varied soil depths, featuring a 20 cm mound near the middle. The green roof at the Nature Center at Shaker Lakes (BE) was designed to mimic a forest understory (Fig. 2d). The one-story flat roof had a rigid modular system that was broken into three sections on the roof, planted with primarily *Aquilegia canadensis* L. (Wild Columbine), *Chrysopsis*

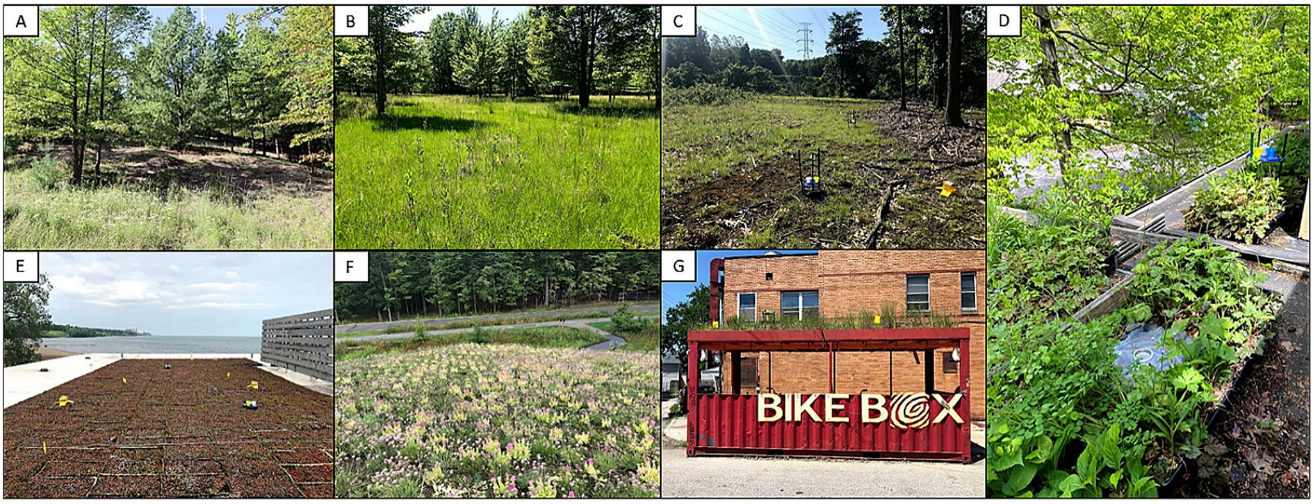

Fig. 2 Ground-level (**A**) Slate shale hill, (**B**) Dusty Goldenrod meadow, (**C**) Bedford barren, and green roof sites (**D**) Nature Center at Shaker Lakes, (**E**) Edgewater beach house, (**F**) Watershed Stewardship Center, (**G**) Happy Dog Bike Box

mariana (L.) Elliott (Golden Aster), *Geranium maculatum* L. (Wild Geranium), *Heuchera americana* L. (Coral Bells), *Solidago flexicaulis* L. (Zigzag Goldenrod), and *Thalictrum dioicum* L. (Early Meadow-rue), among other species. On the ground-level it was surrounded by similar native plant landscaping, a wooded park, and wetland. These modular systems were initially deeper than on the SE roofs, but the substrate has settled in the over 15 years since establishment. All green roofs except Edgewater Beach House were examined by Droz et al. (2022, 2021), detailing additional properties of the roofs and adjacent ground-level land.

Field and laboratory methods

Sampling began in 2019. Due to the COVID-19 pandemic and associated travel restrictions in 2020 this experiment was placed on hiatus. In 2021 we resumed sampling. The thin soil at the ground-level and green roof sites of interest constrained how we were able to monitor the insects. From a conservation standpoint, disturbing ground-level thin soil habitats is undesirable, because limited substrate is available in these habitats. Additionally, many extensive green roofs cannot be disturbed as it would impact the expensive structural elements below the substrate such as waterproofing membranes. Due to these constraints, all sampling had to be done above the surface level.

In 2019 insects were trapped using three types of passive sampling traps: sticky cards (Pherocon, Zoecon, Palo Alto, CA, USA), bee bowls (also known as pan traps, inspired by Leong and Thorp 1999), and yellow ramp traps (ChemTica Internacional S.A., Santo Domingo, Costa Rica), evenly spaced at each site for 48 h once per month for June, July and August (Supplementary Material – Table 1). In 2021, after a trap calibration experiment (McNamara Manning et al. 2022), yellow ramp traps were replaced with a novel trap design which was more targeted at capturing ground-dwelling insects, which we refer to here as the jar ramp trap. Additionally, the months of May and September were added to the protocol to capture insects active during the beginning and end of the growing season. In 2021 we reduced the number of traps per site to limit oversampling and ensure sampling evenness across sites. All sites were sampled with two of each trap type except for the Happy Dog Bike Box which could not support this many traps due to its small area (13.935 m^2) and instead had one jar ramp trap and one bee bowl (Supplementary Material – Table 1).

The trap types were chosen to target insects that provide the relevant ecosystem services, while gaining insights into factors structuring the entire insect community. The bee bowls, consisting of an array of three colored bowls (blue, yellow, and white), were adjusted to the height of the plant canopy and filled with soapy water, collecting flying insects, and targeting pollinators. The sticky cards were approximately one foot off the ground, collecting flying insects, and targeting predators and parasitoids, insects most associated with pest control services. The yellow ramp traps or jar ramp traps were placed on the ground and filled with soapy water, collecting ground-dwelling insects, targeting predators. Bowls, ramps, and jar ramps were filled with soapy water (Dawn Original Liquid Dish Soap, Procter & Gamble, Cincinnati, OH, USA), to break the surface tension. Bowls and yellow ramp traps were strained in the field with fine mesh upon collection and placed in a gallon zipper top bag with ethanol. Jars had a lid screwed on to secure the sample. Sticky cards were placed directly into gallon zipper top bags. In the lab, the liquid samples were strained, identified and placed in vials with 70% ethanol for storage. The sticky cards were frozen and identified while remaining in the bag.

Specimens were identified to order, superfamily, group ("wingless parasitoid wasps"), or family. This was modeled after studies that used this mixed approach of identifying for insect functional classifications such as natural enemy or herbivore (Fiedler and Landis 2007; Gibson et al. 2019), or predators (Hermann et al. 2019; Mabin et al. 2020). Specimens were classified into groups of pollinators, natural enemies, or other. Taxa identified as Apoidea: Anthophila, Lepidoptera, and Syphridae were classified as pollinators (Herrmann et al. 2023). Taxa identified as Anthocoridae, Cantharidae, Carabidae, Chalcidoidea, Coccinellidae, Ichneumonoidea, Neuroptera, Reduviidae, Syrphidae, and wingless parasitoid wasps were classified as natural enemies, which is a classification made up of predators and parasitoids (Gibson et al. 2019). Note that syrphids (hoverflies) were classified as both pollinators and natural enemies (many immatures belonging to this family are predaceous, while adults are nectar feeders) (Skevington et al. 2019).

Statistical methods

All statistical analyses were completed using R 4.2.2 (Core Team 2022). Data were evaluated for statistical assumptions of normality and homogeneity of variance. Taxonomic richness (number of taxa per trap) and Shannon diversity index (Hill 1973) were calculated using the *vegan 2.6-4* package (Oksanen et al. 2022).

Linear mixed effects models were developed to examine differences in insect communities between green roof and ground-level habitats, using the packages *lme4* (Bates et al. 2015) and *lmerTest* (Kuznetsova et al. 2017). The response variables examined were insect taxa richness and Shannon diversity. Each model included sampling date, habitat (green roof or ground-level), and type of trap (yellow sticky card, yellow ramp trap, jar ramp trap, or bee bowl) as categorical fixed effects and trap number nested within site as a random effect: *Response variable ~ Date + habitat + Trap + (1|Site:Replicate)*. The same models were performed on only the green roof sites, replacing the variable 'habitat' with 'design' to compare between green roof design types (SE or BE): *Response variable ~ Date + design + Trap + (1|Site:Replicate)*. Tukey pairwise comparisons between site or design types, as well as trap type were performed using the *emmeans 1.8.5* package (Lenth et al. 2023) for all models.

To characterize the insect communities, we used non-metric multidimensional scaling (NMDS, with Jaccard distance) (Oksanen et al. 2022). NMDS was used to compare four separate classification schemes for the insect communities: green roof and ground-level habitats, green roof design types: SE and BE, ground-level habitats and SE green roofs, and ground-level habitats and BE green roofs. For this analysis we used presence-absence data pooled by site for each sampling date. Permutational multivariate analysis of variance (PERMANOVA) and analysis of multivariate homogeneity of group dispersions using betadisper were performed following each NMDS analysis to assess compositional dissimilarity between habitat or design type (Oksanen et al. 2022). With the green roof insect community NMDS we also compared each of the four green roof sites using the *pairwiseAdonis 0.4* package (Martinez Arbizu 2020).

To evaluate beneficial insects, linear mixed effects models were used to examine differences in pollinator and natural enemy taxa between green roof and ground-level habitats and between green roof design types. The response variables examined were beneficial insect taxa richness and Shannon diversity, modeling pollinators and natural enemies separately. Each model included sampling date, habitat (green roof or ground-level), and type of trap (yellow sticky card, yellow ramp trap, jar ramp trap, or bee bowl) as categorical fixed effects and trap number nested within site as a random effect: *Response variable ~ Date + habitat + Trap + (1|Site:Replicate)*. The same models were performed on only the green roof sites, replacing the variable 'habitat' with 'design' to compare between green roof design types (SE or BE): *Response variable ~ Date + design + Trap + (1|Site:Replicate)*. Tukey pairwise comparisons between habitat or design type, as well as trap type were performed for all models (Lenth et al. 2023).

Results

In total we collected and identified 42,503 insect specimens: 14,565 specimens from the four green roof sites and 27,938 from the three ground-level sites. Hemiptera was the most abundant order in the green roof habitat, with Aphididae (aphids) as the most abundant family. Between the two green roof design types, there was a greater total abundance of aphids on SE (4,900) than BE (598) green roofs. Diptera (flies) was the most abundant order in the ground-level habitat (Table 1). In the 1.5 km radius around each site percent greenspace was approximately 31% (Bedford barren), 29% (Slate shale hill), 25% (Watershed Stewardship Center), 14% (Edgewater beach), 12% (Happy Dog bike box and Nature Center at Shaker Lakes), and 2% (Dusty goldenrod meadow) (Supplementary Material – Table 2).

Insect community analyses

Overall, ground-level habitats had statistically greater insect richness than the green roof habitats (5.52 ± 0.30; 4.66 ±

Table 1 Insect abundances, total (T) and standardized (S), by habitat. Total is the raw abundance collected during the study. Standardized abundances represent the average number of insects collected per trap during the study. Standardized abundances were calculated by dividing total abundances by the total number of traps used in that habitat, green roof or ground-level, during the length of the study

			Green roof		Ground-level	
			T	S	T	S
Blattodea		Cockroaches and termites	0	0	1	0.01
Diptera		Flies	4557	20.07	19,586	98.92
	Syrphidae *†	Hoverflies	250	1.10	359	1.81
	Other Dipterans		4307	18.97	19,227	97.11
Hymenoptera		Sawflies, wasps, bees & ants	810	3.57	1195	6.04
	Apoidea: Anthophila *	Bees	78	0.34	291	1.47
	Chalcidoidea †	Chalcid wasps	538	2.37	674	3.40
	Ichneumonoidea †	Braconid & Ichneumonid wasps	86	0.38	138	0.70
	Formicidae	Ants	89	0.39	69	0.35
	Other wasp		14	0.06	20	0.10
	Wingless parasitoid †		5	0.02	3	0.02
Hemiptera		True bugs	6462	28.47	6500	32.83
	Adelgidae	Adelgids	6	0.03	0	0
	Aleyrodidae	Whiteflies	559	2.46	170	0.86
	Anthocoridae †	Minute pirate bugs	13	0.06	3	0.02
	Aphididae	Aphids	5498	24.22	6028	30.44
	Cercopidae	Froghoppers	8	0.04	12	0.06
	Cicadellidae	Leafhoppers	248	1.09	222	1.12
	Fulgoroidae	Planthoppers	0	0	3	0.02
	Membracidae	Treehoppers	40	0.18	3	0.02
	Miridae	Plant bugs	42	0.19	1	0.01
	Pentatomidae	Stink bugs	2	0.01	0	0
	Psyllidae	Jumping plant lice	26	0.11	28	0.14
	Reduviidae †	Assassin bugs	0	0	1	0.01
	Tingidae	Lace bugs	0	0	1	0.01
	Unknown Hemipteran		20	0.09	28	0.14
Coleoptera		Beetles	191	0.84	227	1.15
	Cantharidae †	Solider beetles	18	0.08	22	0.11
	Carabidae †	Ground beetles	1	0.004	3	0.02
	Chrysomelidae	Leaf beetles	32	0.14	52	0.26
	Coccinellidae †	Lady beetles	17	0.07	16	0.08
	Curculionidae	Weevils	10	0.04	24	0.12
	Elateridae	Click beetles	2	0.01	1	0.01
	Lampyridae	Fireflies	7	0.03	1	0.01
	Mordellidae	Tumbling flower beetles	20	0.09	43	0.22
	Scarabaeidae	Scarab beetles	1	0.004	8	0.04
	Staphylinidae	Rove beetles	7	0.03	4	0.02
	Unknown Coleoptera		76	0.33	53	0.27
Lepidoptera *		Butterflies and moths	11	0.05	32	0.16
Neuroptera †		Lacewings, mantidflies, antlions	2	0.01	3	0.02
Orthoptera		Grasshoppers, crickets, katydids	152	0.67	29	0.15
Psocodea		Bark, book, and parasitic lice	15	0.07	2	0.01
Thysanoptera		Thrips	2361	10.40	361	1.82
Trichoptera		Caddisflies	4	0.02	2	0.01

Note: * denotes pollinator, †denotes natural enemy

0.28, $p = 0.01$). There was no difference in Shannon diversity between the green roof and ground-level habitats (0.95 ± 0.05; 0.91 ± 0.05, $p > 0.05$) (Fig. 3a). When examining the green roofs functional intent design types, SE and BE, there was no difference in insect taxa richness or Shannon diversity (richness: 4.79 ± 0.41; 4.29 ± 0.46, $p > 0.05$; Shannon diversity: 0.81 ± 0.06; 0.94 ± 0.07, $p > 0.05$) (Fig. 3b).

All non-metric multidimensional scaling analyses found strong overlap in insect communities, although some comparisons were statistically different. The PERMANOVA following the NMDS of the total insect community (stress = 0.20) found statistical differences in the insect communities between green roof and ground-level habitats (p = 0.001; Fig. 4a). Homogeneity of multivariate dispersion could not be assumed, indicating that the green roof sites are more different from one another than the ground-level sites. The PERMANOVA following the NMDS of the green roof insect community (stress = 0.16) found no difference between SE and BE green roof design types (p = 0.60; Fig. 4b) and homogeneity of multivariate dispersion was assumed. Pairwise PERMANOVA also found no difference between any of the green roof sites (p > 0.05). The PERMANOVA following the NMDS of the ground-level habitat and SE green roof insect communities (stress = 0.18) found statistical differences between the communities at the ground-level habitat and on SE green roofs (p = 0.01; Fig. 4c). Homogeneity of multivariate dispersion could not be assumed, indicating that SE green roof sites are more different from one another than the ground-level sites. The PERMANOVA following the NMDS of the ground-level habitat and BE green roof insect communities (stress = 0.18) found statistical differences between the community at the ground-level habitat and on BE green roofs (p = 0.001; Fig. 4d) and homogeneity of multivariate dispersion was assumed.

Beneficial insect analyses

In ground-level habitat we captured 682 pollinator specimens and 1222 natural enemy specimens. In the green roof habitat we captured 339 pollinator specimens and 930 natural enemy specimens. Of the green roof design types, SE roofs had a greater abundance of both pollinators and natural enemies (236 and 556), than BE roofs (103 and 341) (Table 2).

We found statistically greater mean pollinator richness (0.74 ± 0.05, p = 0.0001) and Shannon diversity (0.11 ±

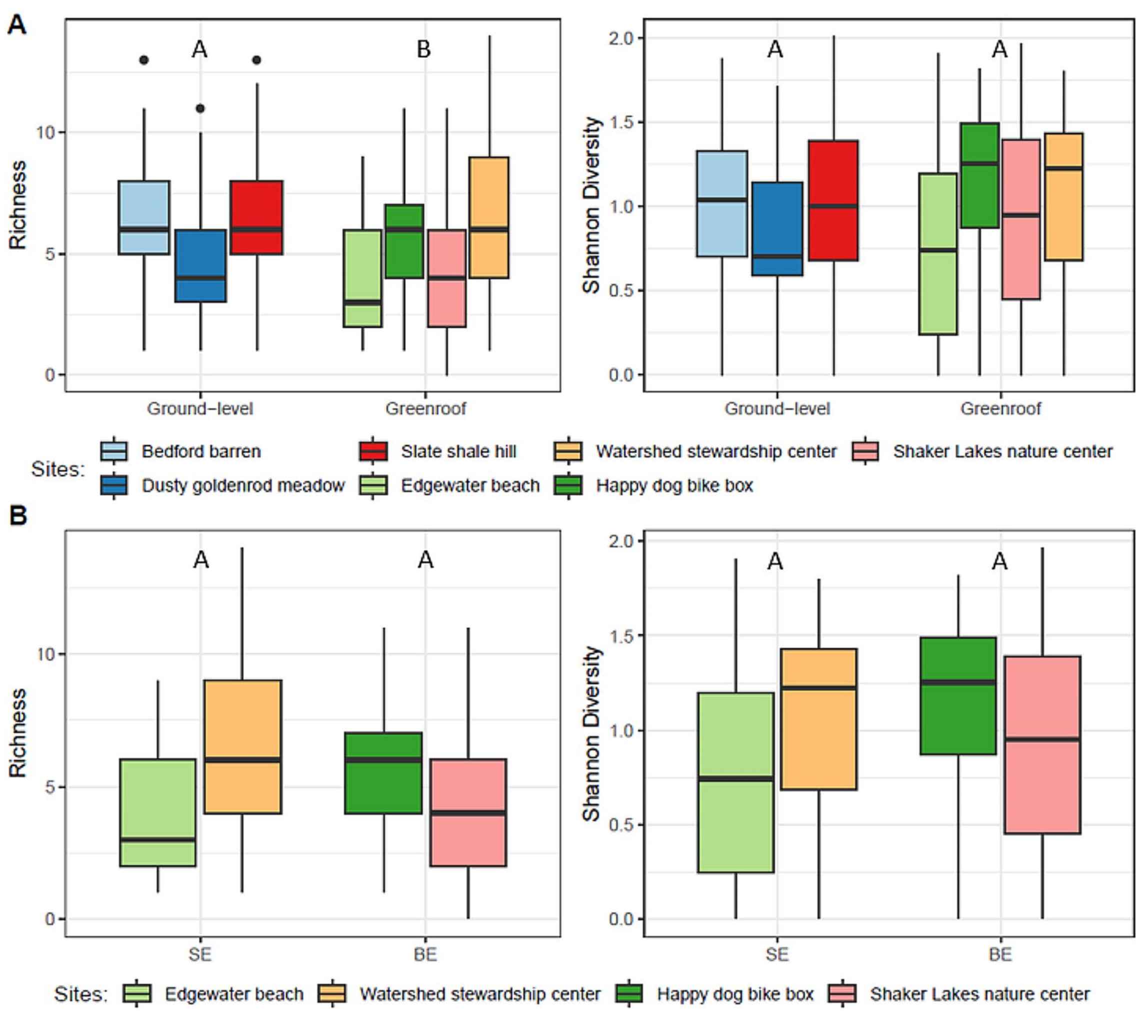

Fig. 3 Box plots comparing taxa richness and Shannon diversity of insect communities in each site grouped by habitat: ground-level and green roof (**A**) and green roof design type: Stormwater-energy (SE) and Biodiversity-ecological (BE) (**B**). Letters shared indicate no statistical difference in estimated marginal means by Tukey method, P > 0.05

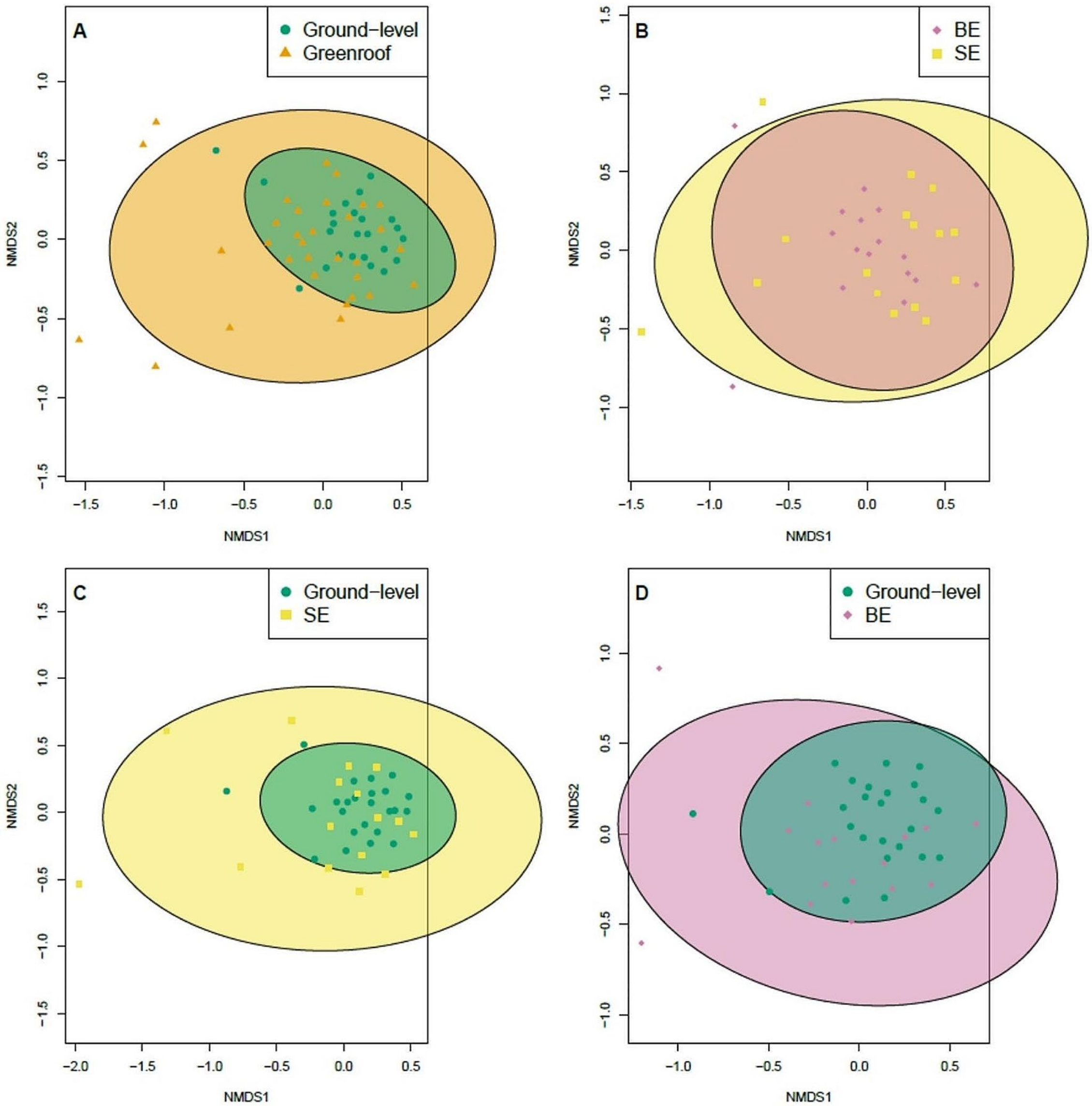

Fig. 4 Non-metric multidimensional scaling figures representing insect communities by habitat: ground-level and green roof (**A**: stress = 0.20, p = 0.001); green roof design type: Stormwater-energy (SE) and Biodiversity-ecological (BE) (**B**: stress = 0.16, p = 0.60); ground-level habitat and SE roof (**C**: stress = 0.18, p = 0.01) and BE roof (**D**: stress = 0.18, p = 0.001)

0.02, $p = 0.001$) at ground-level than green roof (0.44 ± 0.05; 0.05 ± 0.01) habitats (Fig. 5). Bee bowls captured statistically greater mean pollinator richness and diversity than the other trap types ($p < 0.0001$). Comparing pollinators between SE and BE green roofs, we found no difference in mean pollinator richness (0.49 ± 0.07; 0.41 ± 0.08, $p > 0.05$) and Shannon diversity (0.06 ± 0.02; 0.04 ± 0.02, $p > 0.05$) (Fig. 5). The trap comparisons produced the same results: bee bowls captured statistically greater mean pollinator richness and diversity than the other type types ($p < 0.0001$).

We found statistically greater mean natural enemy richness (1.36 ± 0.10, $p = 0.01$) and Shannon diversity (0.28 ± 0.03, $p = 0.01$) at ground-level than green roof (1.02 ± 0.09; 0.16 ± 0.03) habitats (Fig. 5). Bee bowls captured the greatest mean natural enemy richness and diversity, but they were only statistically greater than yellow ramp traps ($p = 0.01$). Sticky cards also captured statistically greater mean natural enemy richness than yellow ramp traps ($p = 0.01$). Comparing natural enemies between SE and BE green roofs we found no difference in mean natural enemy richness (1.14 ± 0.14; 0.90 ± 0.14, $p > 0.05$) or Shannon diversity (0.18 ± 0.03; 0.12 ± 0.04, $p > 0.05$) (Fig. 5). There was no difference in catch between any of the trap types for natural enemy richness or diversity ($p > 0.05$).

Table 2 Beneficial insect abundances, total (T) and standardized (S), by ground-level habitat and green roof design type. Total is the raw abundance collected during the study. Standardized abundances represent the average number of insects collected per trap during the study. Standardized abundances were calculated by dividing total abundances by the total number of traps used in that category during the length of the study

		Green roof				Ground-level	
		SE		BE			
		T	S	T	S	T	S
Natural enemies		556	4.41	341	3.38	1222	6.17
Anthocoridae	Minute pirate bugs	12	0.10	1	0.01	3	0.02
Cantharidae	Solider beetles	18	0.14	0	0.00	22	0.11
Carabidae	Ground beetles	1	0.01	0	0.00	3	0.02
Chalcidoidea	Chalcid wasps	284	2.25	235	2.33	674	3.40
Coccinellidae	Lady beetles	14	0.11	2	0.02	16	0.08
Ichneumonoidea	Braconid & Ichneumonid wasps	38	0.30	35	0.35	138	0.70
Neuroptera	Lacewings, mantidflies, antlions	1	0.01	1	0.01	3	0.02
Reduviidae	Assassian bugs	0	0	0	0.00	1	0.01
Syrphidae	Hoverflies	188	1.49	62	0.61	359	1.81
Wingless parasitoid		0	0	5	0.05	3	0.02
Pollinators		236	1.87	103	1.02	682	3.44
Apoidea: Anthophila	Bees	41	0.33	37	0.37	291	1.47
Lepidoptera	Butterflies and moths	7	0.06	4	0.04	32	0.16
Syrphidae	Hoverflies	188	1.49	62	0.61	359	1.81

Discussion

In examining the insect communities on extensive green roofs and similarly structured ground-level habitats we found that both habitats supported diverse insect communities, including beneficial insects. As predicted, the ground-level habitat possessed greater insect taxa richness than green roof habitat. However, we observed no difference in Shannon diversity between ground-level and green roof habitats. This finding is similar to other studies that compared green roof and ground-level habitat insect communities, finding insect richness (and abundance (MacIvor and Lundholm 2011a) greater on the ground-level, but no difference in diversity (Braaker et al. 2017; MacIvor and Lundholm 2011a).

Likely driven by similar mechanisms as the insect community at large, we observed greater taxa richness and Shannon diversity of both pollinators and natural enemies at ground-level habitat. Although, there were relatively low numbers collected, especially of pollinators. This finding is similar to studies by Tonietto et al. (2011) in Chicago, IL, USA and Colla et al. (2009) in Toronto, Ontario, Canada that found greater bee richness and diversity at ground-level sites than on green roofs. Green roofs provide habitat for bees (Colla et al. 2009; Passaseo et al. 2020, 2021; Tonietto et al. 2011) and hoverflies (Passaseo et al. 2020, 2021), but perhaps to a lesser extent for hoverflies (Jacobs et al. 2023). Although we found almost 70% more hoverflies than bees at our green roof sites. Similar to our study, green roofs have also been shown to support biocontrol agents such as parasitoid wasps (Diethelm and Masta 2022), and predators and parasitoids in general (Fabián et al. 2021; Sánchez Domínguez et al. 2020).

Generally, the design of the green roof did not influence the insect community or its relationship to the ground-level habitat. The biodiversity-ecological (BE) oriented green roofs were designed as analogs to prairie or forest understory, and thus have varied plant taxa between them. In general, the stormwater-energy (SE) green roofs had very similar plant communities as they were both planted with mostly non-native *Sedum* species. It would be expected that if plants alone defined the insect community using a space, then BE green roofs would be more similar to ground-level communities. Yet, despite the difference in intent and plant communities, the green roof design types had similar insect communities and no difference in insect taxa richness or Shannon diversity between any of the green roof sites. This finding is similar to Jacobs et al. (2023), which found no difference in insect communities between green roofs with *Sedum* and roofs with *Sedum* mixed with other vegetation. MacIvor (2016) found that increasing height and decreasing surrounding greenspace contributed to lower bee and wasp species richness and abundance, which could help explain our findings.

SE and BE green roofs had similar biodiversity metrics for beneficial insects, and there was a greater abundance of pollinators and natural enemies on SE green roofs. This observation may be related to a prevalence of flowering plants on the SE roofs, despite their non-native status. It has been shown that bees can use *Sedum* flowers for foraging,

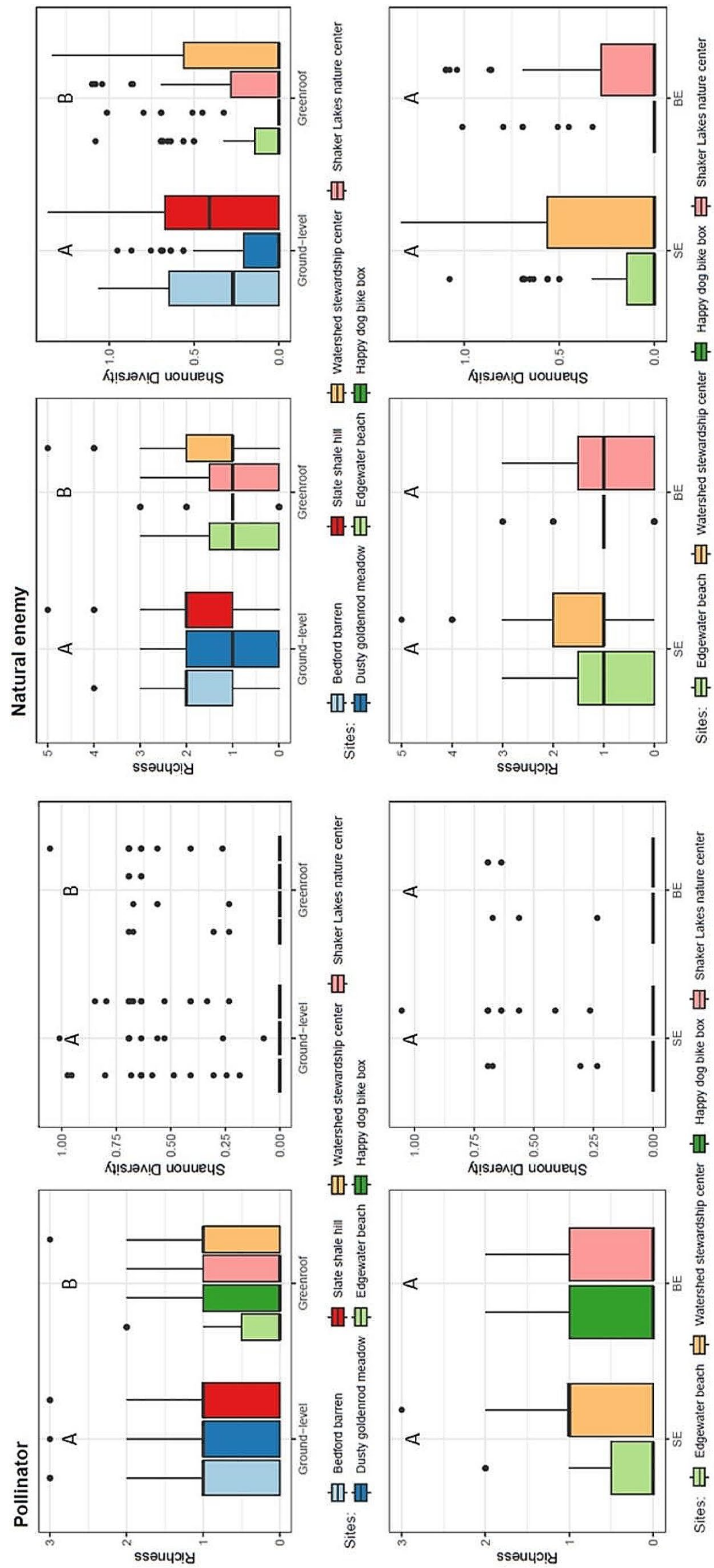

Fig. 5 Box plots comparing taxa richness and Shannon diversity of beneficial insect (pollinators and natural enemies) communities in each site grouped by habitat: ground-level and green roof and green roof design type: Stormwater-energy (SE) and Biodiversity-ecological (BE). Letters shared indicate no statistical difference in estimated marginal means by Tukey method, P > 0.05

but exotic bees had greater pollen loads than natives, thus vegetation on green roofs could shape the urban bee community that inhabits or forages on them (MacIvor et al. 2015). Potentially contributing to natural enemy abundance in our study, SE roofs supported a much higher abundance of aphids, a common agricultural pest insect (Emden and Harrington, 2017; Miller and Foottit 2009), which is typically preyed upon by the natural enemy *Coccinellidae* (lady beetles). Nearly 5,000 aphids were captured over the course of the study on SE roofs while on BE green roof captures of this taxa were an order of magnitude lower. Aphids have been observed on other extensive, *Sedum* green roofs (MacIvor and Ksiazek 2015), sometimes in abundance (Coffman and Waite 2011), and notably lady beetles are often spotted as well (Appleby-Jones 2014; Kadas 2006).

The two sites with the greatest surrounding greenspace were ground-level habitats: Bedford barren and slate shale hill. The former is within the Cuyahoga Valley National Park and the latter a metro park reservation. However, the third ground-level habitat, dusty goldenrod meadow had the lowest surrounding greenspace of all sites. The dusty goldenrod meadow is surrounded by a dense residential area. These yards may provide some resources for insect communities, but it is not the same as the greenspace surrounding the other two ground-level sites, which are larger parks. This site also had the lowest insect richness and diversity among the ground-level sites. Though the Happy Dog bike box green roof does not have much greenspace directly surrounding, as it is in downtown Cleveland, the 1.5 radius does reach to a metro park reserve near the lakeshore, adding to the greenspace percentage and making it about equal with the Nature Center at Shaker Lakes green roof which is within a park. The Edgewater beach green roof sits in the metro park reservation near the bike box green roof. These two green roofs have overlapping radii, leading us to believe that insects could travel between these two green roofs. Lastly, the Watershed Stewardship Center has the greatest surrounding greenspace of the green roof habitats. It is surrounded by floral resources and sits within the same metro park reservation as the slate shale hill, hence the overlap of radii, which again means that insects should be able to travel between these habitats.

Conclusions

Using vegetated infrastructure, such as green roofs, could expand insect habitat in fragmented urban landscapes that have lost some habitat due to urbanization (Brenneisen 2003, 2006; Colla et al. 2009; Lundholm 2006; MacIvor and Lundholm 2011a; Tonietto et al. 2011). Though community metrics differed between green roof and ground-level habitats in our study, we do show that both habitat types support insects, including the beneficial insects, pollinators and natural enemies. Having the goal of increasing biodiversity in mind when designing green roofs is beneficial, but in some cases, simply having the resources provided by a novel habitat patch may be sufficient to support insects. Even when roofs are designed for primarily other benefits, such as stormwater management and energy reduction, they may still provide habitat for insects (Coffman and Davis 2005; MacIvor et al. 2015). However, examining insect services is critical to supporting conservation decision-making in these human-managed ecosystems and providing supportive and diverse habitat for beneficial insects that will bring pollination and pest control to the urban environment is important to think about when designing green roofs (Tonietto et al. 2011).

Integrated ecology and architecture research offers a unique opportunity to advance both basic understanding of community assembly in novel environments and to drive the human benefits associated with the biodiversity of living architecture. Our study used a relatively small number of green roofs, of two design types. Increasing the sample size or including similar types across cities occurring in different locations could provide researchers with more information on the ability of green roofs to provide habitat for insects, as well as design elements to incorporate. More work on beneficial insects and green roof design could be valuable to humans by potentially increasing the services of pollination and pest control, on top of the benefits that urban areas already receive from this infrastructure. Identifying the beneficial insects captured to species could tell us specifically who is being supported by these habitats and green roof design types. Also examining which plants are being visited by the beneficial insects could be informative for design. For example, taking pollen samples from pollinators at the habitats could help discern which floral resources they are utilizing. Additionally, though all sites are in an urban matrix of human-disturbed habitat, the landscape around each site differed and with that, the amount of greenspace around each site and the connectivity of that habitat to others. Further examining the impervious surfaces, vegetation, and other factors about the area adjacent to our study sites could reveal more patterns.

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Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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