ABSTRACT

LARSEN, SAMANTHA RUTH. A Comparison of Beneficial Arthropod Communities in Urban Bioretention Cells and Ornamental Landscapes. (Under the direction of Dr. Steven D. Frank and Dr. Clyde S. Sorenson).

Bioretention cells are designed to provide regulating ecosystem services, such as moderation of flooding, pollution control, and carbon sequestration, in urban environments. They look like ornamental urban landscapes but are specially designed to reduce flooding and stream pollution. Our goal was to determine if bioretention cells serve dual functions by providing stormwater control services, while maintaining or increasing biodiversity of beneficial arthropods in urban landscapes. To achieve this, we sampled predators, parasitoids, and detritivores in engineered bioretention cells (bio-cells) and in ornamental landscapes to compare arthropod communities using three different trapping methods: yellow sticky cards, vacuum sampling, and pitfall traps. Sticky card sampling showed that natural enemies in the order Hemiptera (which included Anthocoridae, Geocoridae, Nabidae, and Reduviidae) were significantly more abundant in landscape sites for 2016, as were spiders in 2017. The collection height affected total predators in 2016 and parasitoid wasps and Coleoptera (Coccinellidae and Staphylinidae) both sampling years, all of which were significantly more abundant at 0.5m trapping height, but in 2017 significantly more spiders were found at 1.5m sampling height. Greater plant diversity significantly increased total predators, parasitoid wasps and Coleoptera in 2016 and Diptera (Asilidae, Dolichopodidae, and Syrphidae) during both sampling years. Vacuum sampling showed significantly more spiders in bio-cells during 2016. Landscapes had significantly more Hemiptera in 2016 and significantly more natural enemies in the total predators, spiders and other categories in 2017. Significantly fewer natural enemies in the other category were found in 2016 where plant species diversity was increased, but significantly more parasitoid wasps were found in 2017. There were no significant differences in the natural enemy abundance detected through pitfall trapping. Although some significant differences were found between the natural enemies in bio-cells and landscapes, the majority of natural enemy communities were similar. Bio-cells perform dual functions in urban environments by serving as habitat for natural enemies and detritivores as well as providing control and remediation of stormwater pollution. We also found that increasing the plant diversity within bio-cells can help to increase the number of predators and pollinators in urban landscapes. Bio-cells are becoming more common in urban landscapes, and their value for increasing arthropod diversity and ecosystem services will be an important part of future landscape planning and management. (367/600)

A Comparison of Beneficial Arthropod Communities in Urban Bioretention Cells and Ornamental Landscapes.

by
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BIOGRAPHY

"Look deep into nature, and then you will understand everything better"

-Albert Einstein

Any scientist knows that the world is infinitely more complex than can be understood, but the tiny glimpses gleaned are the joy of life. As an entomologist, Samantha Larsen enjoys taking a closer look at the delightful intricacies of insect life. She began her journey as an entomologist at a very young age, picking up grasshoppers and caterpillars with her younger brother in Northwest Arkansas. As a senior in high school, Samantha was very passionate about agriculture and sustainability, and for an FFA competition wrote an essay on entomophagy, which sparked her interest in insects as a food source. To pursue her interest in insects as a sustainable food source, she majored in entomology at Oklahoma State University (Go Pokes!), before graduating and taking the opportunity to move across the country and further her knowledge at North Carolina State University. North Carolina has opened new doors and Samantha is looking forward to many more adventures and glimpses of joy in the future.

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"No duty is more urgent than that of returning thanks"

-James Allen

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COMPARISON OF BENEFICIAL ARTHROPOD COMMUNITIES IN URBAN BIORETENTION CELLS AND ORNAMENTAL LANDSCAPES

1. Introduction

The United Nations estimated that as of 2016, 54.5 percent of humans lived in cities (United Nations 2016). In the United States that percentage is even higher, with over 80 percent of US residents living in urban areas (Berg 2012). Because of the high demand for city living, natural or agricultural landscapes have been converted into areas of man-made infrastructure through a process known as urbanization (Wagner 2008). Urban ecosystems are characterized by highly fragmented landscapes that are heterogeneous and temporally dynamic with large amounts of impervious surface, pollution, and changes in local climate (Grimm et al 2008). Urbanization has caused worldwide loss of habitat, biodiversity, and ecosystem services (McKinney 2002, Liu et al. 2016). Despite this, urban environments are considered to be ecosystems and perform many ecosystem services (Gardner et al 2014), including regulating services, which shape the climate, water, and air quality (Green et al 2015). Regulating services, such as carbon sequestration, flooding moderation, wastewater treatment, erosion prevention, pollination, and biocontrol, are especially important in urban environments because they protect air and water quality (TEEB, Eigenbrod et al 2011).

Vegetation removal, soil compaction, and impervious infrastructure can increase stormwater runoff and cause flooding and pollution of local streams and watersheds (Booth and Jackson 1997, Dietz 2007). In addition, increasing magnitudes and frequency of rainfall due to climate change may exacerbate the effects of urbanization by increasing the volume of untreated and uncontrolled run off (Semadeni-Davies et al. 2008, Hathaway et al. 2014). To mitigate the loss of these regulating ecosystem services in cities, the United States Environmental Protection Agency (EPA) now requires that cities implement stormwater control measures to reduce water pollution (EPA 2017, NRC 2008). Non-structural stormwater control measures, such as street sweeping and point source pollution prevention, and structural stormwater control measures, such as wet or dry bioretention cells (rain gardens), bioswales, green roofs, pervious pavement, and rainwater retention cisterns, are designed to reduce flooding, limit erosion pollution, and lower peak discharge rates of water into sensitive stream environments (Dietz 2007, Barbosa et al 2012, Hunt et al 2012). All structural stormwater control measures provide regulating services, but those measures that include plants are becoming more prevalent in many cities because of their ornamental appeal (Hunt et al 2006) and ability to restore or maintain predevelopment hydrology (Davis et al. 2009). Furthermore, the incorporation of plants into bioretention cells may provide other benefits, such as pollination and biological control, by attracting and providing food and habitat for beneficial arthropods.

Dry bioretention cells (bio-cells) are a unique opportunity to conserve insect biodiversity and habitat in addition to providing other critical ecosystem services in cities. Bio-cells are a type of structural stormwater control measure designed to reduce nonpoint source pollutants, such as metals, oil and excess nutrients, and to reduce stormwater velocity, allowing water to infiltrate the soil and recharge groundwater reserves (Hunt et al 2012). Bio-cells are man-made depressions in the ground partially filled with layers of native soils and imported material to provide infiltration, evapotranspiration, and pollutant removal (Hathaway et al. 2014). This substrate is planted with vegetation and covered with bark mulch to provide weed control and retain moisture for plants (Dietz and Clausen 2005, Le Coustumer et al 2012). Since bio-cells are designed to capture and filter pollutants from runoff water, fertilizer and pesticide applications are highly discouraged (Hunt 2012, NCDEQ 2017). Thus, low-maintenance native and non-native plants are selected for this application and to improve water quality. The potential for plant choice to affect arthropod diversity and conservation in bio-cells has thus far received little attention (Kezemi et al. 2009, Mehring and Levin 2015).

Conservation of beneficial arthropods in urban landscapes is imperative for pollination (Levin 1983, Samways 2005), decomposition (Kezami et al. 2009, Ossola et al. 2016), and pest regulation (Gardiner et al. 2014) in yards, golf courses, parks and other urban greenspaces (Bennett and Gratton 2013). Increasing plant diversity and structural complexity can increase beneficial arthropod abundance and diversity by providing food and habitat resources (Landis et al. 2000, Bennet and Gratton 2013, Blaauw and Isaacs 2015, Gurr et al. 2016). Flowering plant species, which provide nectar and pollen, are particularly important for sustaining parasitoid abundance and fecundity (Tena et al. 2015) as well as omnivorous predators such as lady beetles, syrphid flies, rove beetles, and minute pirate bugs (Bennett and Gatton 2013, Wong and Frank 2013, Gardiner et al. 2014). Plant species without floral resources, such as bunch grasses, are important for the conservation of ground dwelling predators such as ground beetles and spiders that use them for refuge and overwintering habitat (Frank and Shrewsbury 2004, Frank et al 2008). In some cases, increasing plant diversity or adding particular floral species can increase biological control of pests in urban landscapes (Frank and Shrewsbury 2004, Shrewsbury and Raupp 2006, Bennett and Gratton 2013, Jonsson et al. 2015).

Habitat area has long been considered a driving factor in floral and faunal diversity (Connor and McCoy 1979). As in other habitats, abundance and diversity of beneficial arthropods in urban landscapes generally increases with larger habitat size and greater plant diversity (McIntyre et al., 2001, Tscharntke et al. 2007, Raupp et al., 2010), and these landscape factors could affect the communities of beneficial arthropods within cities. Previous studies assessing invertebrate communities in vegetated structural control installations have found that even small, relatively new bio-cells (Kezami et al. 2009) and green roofs (Braaker et al 2014) offer potential as suitable habitat.

As urbanization increases, it is imperative to protect water quality from pollution, and the use of bio-cells achieves this objective while maintaining greenspace in urban environments. Bio-cells are thus becoming more common in urban landscapes and understanding their value for increasing arthropod diversity and ecosystem services is an important part of future urban landscape planning and management. Our goal was to determine if bio-cells serve dual functions by maintaining or sustaining beneficial arthropod populations in urban environments, in addition to providing the stormwater control services for which they were designed. We sampled natural enemies and detritivores in bio-cells, and in ornamental landscapes that were chosen based on area and number of plant species, to compare abundance within these different urban environments. Our specific objectives were (i) to determine if bio-cells harbored comparable or greater numbers of natural enemies (parasitoid wasps and predators) and detritivores than ornamental landscapes, and (ii) to determine if bio-cell area and plant diversity interact to affect natural enemy and detritivore abundance in bio-cells.

2. Methods

2.1 Study Sites

The study took place in Raleigh, North Carolina, USA from May-September in 2016 and March-August in 2017 on the campus of North Carolina State University (35.7847° N, 78.6821° W) (See *Figure 1*). Raleigh has a humid, subtropical climate with average annual rainfall of 46.58 inches (US Climate Data 2017). We chose ten bio-cells with areas from $43m^2$ - $457m^2$, and ten ornamental landscape beds with areas from $52m^2$ - $451m^2$; we recorded the number of intentionally planted floral species in each. Ornamental landscapes and bio-cells also had similar levels of shredded hardwood mulch spread evenly over the ground at the start of the sampling season (see supplementary material). Using mapdevelopers.com, we measured the area and perimeter for each bio-cell and ornamental landscape (*Table 1)*. Most of the bio-cell sites are only a few years old, with relatively small trees, and ornamental landscapes were selected with similar amounts of canopy cover and shade.

2.2 Sticky Card Traps

Yellow sticky cards (Olson Products Inc, Medina, OH) were placed at all the sites monthly, from May-September in 2016, and March-July in 2017. We attached an unbaited yellow sticky card (7.62 cm x 12.7 cm) to the end of a bamboo pole 1.5m above the ground, and another to a second pole 0.5m above the ground. For both years, poles were place haphazardly at each site. After 7 consecutive days, we removed the cards, placed them in 4 ml plastic (15.24 cm x 30.48cm) flat open poly bags (Plymor®, Collecting Warehouse, Fairfield, OH), and stored all the cards in the freezer until specimen identification. Bamboo poles were moved before the start of each sampling date. In 2016, sticky cards were placed at sites from 24-31 May, 23-30 June, 26 July-2 August, 23-30 August, and 23-30 September. In 2017, we sampled from 16-23 March, 13-20 April, 16-23 May, 13-20 June, and 23-30 July. Using a dissecting scope, natural enemies were identified to order (Araneae) or to family for insects (Insecta) and classified as predators or parasitoid wasps.

2.3 Vacuum Sampling

To collect arthropods resident in plant foliage, we used a modified Husky Blower Vac (Husqvarna, 125BVX Series) fitted with 15 cm by 70 cm bags made of fine mesh fabric (Crystal Organza, Fabric Exchange, Los Angeles, CA). We sampled all sites monthly from June until August in 2016 and from March until June in 2017. All plant foliage within a square meter of each bamboo pole in the site was vacuumed, including trees vertically up to 1.5 meters. The mesh bags were taken out of the vacuum after each site, closed with a rubber band, and stored in a freezer for at least a week. To identify the natural enemies, we emptied each mesh bag into a separate 90cm petri dish and examined the specimens under a dissecting scope. All predatory arthropods and parasitoid wasps were placed in 70% ethanol. Natural enemies were identified to order for spiders (Araneae) or to family for insects and classified by guild.

2.4 Pitfall sampling

We sampled epigeal arthropods with pitfall traps in bio-cells and ornamental landscapes 1-2 times monthly from March-August in 2017. Pitfall traps were constructed of 16 oz plastic cups (Solo®, Lake Forest, IL) with one empty cup buried slightly below ground level so that the trap would be level with the surface when a second cup was inserted. We placed a second cup containing 2oz of propylene glycol (Ocean Bio Chem Inc®, Starbrite Anti-freeze Antigel, Ft. Lauderdale, FL) inside the first cup for 48 hours to capture epigeal arthropods. After 48 hours, we removed the inner cup containing the antifreeze and replaced it with another cup containing only soil to close the trap between sampling. We brought the sampling cups back to the lab, counted the arthropods under a dissecting scope and placed all predators, parasitoids and detritivores in 70% ethanol. We identified spiders (Araneae), isopods (Malacostraca), and collembolans (Endognatha) to order and insects to family, then designated each to trophic guild (predator, parasitoid, detritivore).

2.5 Statistical analysis

All statistical analyses were conducted in R version 3.4.1 (R Core Team). We used generalized linear mixed effect models to compare the numbers of natural enemies and detritivores collected via sticky cards, vacuum sampling, and pitfall traps. Models were fitted using the "lme4" (Bates et al. 2015) and "DHARMa" (Hartig 2017) packages. Response variables included: Hemiptera, Diptera, Coleoptera, Hemiptera, Formicidae, detritivores, Araneae, parasitoid wasps, and total predators (which included every family except for Formicidae), and "Other" (which included Odonata, lacewings, and predatory thrips). Generalized linear mixed models were fitted with a negative binomial function to account for the discrete response variables and the non-normal error distributions among the count data. Factors include: site type (bio-cell vs. ornamental landscape) and pole height (short vs. tall bamboo pole). The number of plant species per site was included as a covariate. Sampling month was included as a random effect. Models were run separately for each collection method (yellow sticky cards, vacuum samples, and pitfall traps), year (2016 and 2017) and response variable (arthropod groups).

3. Results

The main objectives of this study were to determine if bio-cells supported equal or greater numbers of natural enemies than ornamental landscapes with similar characteristics and to determine if bio-cell size and plant diversity affected natural enemy abundance. Using generalized linear mixed effects models with a negative binomial function, we found that bio-cells supported similar abundances of natural enemies compared to ornamental landscapes across all sampling methods. When we ran the models to contain both site size and plant diversity, we found that the two factors were correlated, because there were more species of plants in the larger sites. Because of this, we chose plant species as the model variable because bio-cell sites are often unchangeable in size, but landscape planners can choose to plant more floral variety if it increases natural enemy abundance.

3.1 Sticky Card Traps

Site type (bio-cell or ornamental landscape), collection height (1.5 m or 0.5 m above the ground) and number of plant species per site had varying effects on the number of parasitoid wasps and total predators that were collected via yellow sticky cards in 2016 and 2017 (Figure 2). In both years, collection height had a significant effect on the collection of parasitoid wasps, with more wasps collected at 0.5 m than at 1.5 m. Number of plant species had a positive effect on parasitoid wasps in 2016 (Table 2). Similarly, predators were not influenced by site type, but were significantly affected by collection height, with more predators collected at 0.5 m than at 1.5 m, and more with increasing plant diversity in 2016. Hemiptera (which included Anthocoridae, Geocoridae, Nabidae, and Reduviidae) were significantly influenced by site type in 2017, with more collected in ornamental landscapes than in bio-cells. Plant species had a significant positive effect on Diptera (Asilidae, Dolichopodidae, and Syrphidae) in 2016 in that higher plant species diversity attracted higher levels of predatory flies. Coleoptera (Coccinellidae and Staphylinidae) was negatively affected by number of plant species in 2016 and by collection height during both years, with more beetles collected at 0.5m than 1.5m. Spiders were affected by site type and collection height in 2017 with more spiders found on the 1.5m traps in the ornamental landscapes. "Other" (Odonata, lacewings, and predatory thrips) was significantly increased by increasing plant species diversity in 2016 and 2017.

3.2 Vacuum Sampling

Site type (bio-cell or ornamental landscape) and number of plant species per site had varying effects on the number of parasitoid wasps and total predators that were collected via vacuum sampling in 2016 and 2017 (Figure 3). In 2017, the number of plant species had a positive effect on the collection of parasitoid wasps (Table 3). Total predators were influenced by site type in 2017, with more predators collected in the ornamental landscapes than the bio-cells. Site type also influenced the number of spiders (Araneae) in both years. In 2016, there were more spiders found in the bio-cells, but in 2017 more were found in the ornamental landscapes. Hemipterans were also more abundant in ornamental landscapes in 2016. Plant species diversity had a negative effect on "Other" in 2016; however, these also were found significantly more often in ornamental landscapes in 2017. Beneficial Diptera (Asilidae, Dolichopodidae, and Syrphidae) and Coleoptera (Carabidae, Coccinellidae and Staphylinidae) were not significantly different for either year.

3.3 Pitfall Sampling

Detritivores and natural enemies collected with pitfall traps did not differ between bio-cells and ornamental landscape sites (Figure 4 & 5, Table 4). Ants (Formicidae) made up 77.3% of the total ground predators captured using the pitfall traps. Spiders were the second most abundant predator (14.4% of the total predators) and Coleopterans (which included Staphylinidae, and Carabidae) comprised the remaining 8.2% of ground predators. All carabids found in the traps were predatory species; they were most abundant from April to early June. Staphylinids were most abundant in late June, but were primarily found at only 2 sites (VC and Sullivan). Collembolans made up 61.2% of the detritivores collected over all the sites. 32.1% of the detritivores were isopods and the remaining 7.7% of detritivores were Diplopoda, Dermaptera, or Blattaria.

4. Discussion

Urban greenspaces from yards and parks to green roofs and bio-cells can support many beneficial arthropods (McIntyre et al. 2001, Kazemi et al 2009, Braaker et al. 2014, Gardiner et al 2014) and in some cases similar arthropod abundance and diversity to non-urban habitats (Bang and Faeth 2011, Sattler et al. 2011). Bio-cells containing ornamental plantings are increasingly common components of urban landscapes that help reduce water flow and pollutants from storm events. Our results show that bio-cells serve a dual function by supporting similar numbers of natural enemies compared to typical ornamental landscapes. Moreover, we found that natural enemy abundance increases with plant species diversity in bio-cells and ornamental landscapes, which provides a tangible option when designing urban environments with biodiversity conservation in mind.

Beneficial arthropod diversity generally increases with plant diversity and structural complexity (Frank et al. 2008, Bennett & Gratton 2013, Beninde et al. 2015, Turrini and Knop 2015). Arthropod diversity increases because a greater diversity of plants provides a larger variety and distribution of resources (Gurr et al 2004). This relationship forms the basis of conservation biological control tactics in agricultural and urban habitats (Landis et al. 2000). We found that natural enemy abundance was higher in bio-cells and ornamental landscapes with more plant species. This effect was particularly strong for Diptera, wherein Dolichopodidae were over twice as abundant in the bio-cell with the most plant diversity compared to the bio-cell (Goldenleaf) with least number of different plants (Alliance Deck). In ornamental landscape sites, Diptera increased with plant diversity and Dolichopodids were found to be over 10x more abundant in the most plant diverse site (Wolfridge) compared to the least diverse (Greek Sign) over both sampling years.

Plant identity, not just diversity, affects the abundance and diversity of natural enemies in habitats. Plant species can vary greatly in the number, diversity, or timing of parasitoids and predators they attract based on the pollen, nectar, and other resources they provide (Bennett and Gratton 2013). Our work was conducted in existing ornamental landscapes and bio-cells, so we could not manipulate the plant species present. Thus, we could not assess how the presence of particular plant species may affect particular natural enemy taxa. Some plant species were similar between site types but others, such as *Itea virginica*, *Juncus effusus*, and *Cornus sericea*, only occurred in bio-cells, while *Liriope muscari*, *Rosa* x "Radrazz", and *Lagerstroemia indica* only occurred in ornamental landscapes. Little research has been conducted on how these plants affect natural enemies and arthropod communities, except for *L. indica*, which has been shown to support many common predatory arthropods (Mizell III 2007). Plants chosen for bio-cells can bioaccumulate pollutants, but many of the species, including *I. virginica* and *C. sericea* produce flowers which attract pollinators and omnivorous natural enemies. Landscape plants are usually chosen for ornamental value and many of them, including *Liriope muscari* and *Rosa* x “Radrazz” bloom for extended periods of time. Others, such as *Ilex vomitoria*, *Euonymus fortunei* and *Pittosporum tobira* remain green most of the year, which could provide shelter for many arthropods. A study which manipulated floral resource plants found that even without the flowers, natural enemy abundances were greatly increased in landscapes that incorporated floral resources compared to those containing only non-flowering shrubs (Rebek et al. 2005). We did not compare insects on the individual plants, nor did we measure mulch thickness, site maturity, floral abundance or plant density. In a previous study of invertebrate diversity in bio-retention basins in Australia, the authors found that greater plant litter depth and larger numbers of plant taxa increased invertebrate biodiversity (Kazemi et al 2009). These factors, along with plant species choice, could greatly affect arthropod communities and should be the subject of future study.

Biological control is a regulating ecosystem service that has not been previously measured in bioretention cells. We found predators and parasitoids in bio-cells and ornamental landscapes but did not evaluate whether changes in natural enemy abundance, due to habitat type or plant diversity, increased biological control services. However, the groups we sampled, including parasitic wasps, lady beetles, hoverflies, minute pirate bugs, and assassin bugs, have been well documented as beneficial for conservation biocontrol tactics (Bennett and Gatton 2013, Wong and Frank 2013, Gardiner et al. 2014). In the context of conservation biological control, increasing predator and parasitoid abundance is just a first step. As natural enemies become more abundant, they may suppress pest populations and increase biological control (Schaefer and Panizzi 2000, Rebek et al. 2005, Isaacs et al. 2009, Perdikis et al. 2011, Gardiner et al. 2014). In a study that looked at modifying urban habitats to increase parasitism of bagworms, it was found that adding flowering resources around host plants increased parasitism rates by over 70% by attracting greater numbers of adult parasitoid wasps (Ellis et al. 2005).

We did not find consistent differences in foliar and aerial natural enemy abundance between bio-cells and ornamental landscapes. Other research has found that natural enemies generally can differ between habitats such as flower patches (Frank and Shrewsbury 2004), urban community gardens and vacant lots (Gardiner et al 2014), and green roofs (Braaker et al 2014). One long-term study concluded that in urban environments, the type of landscaping and plant choice greatly affects the arthropod communities, which were most likely an assortment of arthropods recruited from the surrounding natural and agricultural landscapes (Bang and Faeth 2011). We found that spiders, "Other", and Hemipteran predators were more abundant in ornamental landscapes than bio-cells. However, in most comparisons natural enemy abundance was similar between ornamental landscapes and bio-cells. Most of the natural enemies in the Coleoptera, Hemiptera, Diptera and parasitoid wasp groupings are quite mobile, and our bio-cells were typically near ornamental landscapes. Many arthropods have high dispersal capabilities (Chapman et al. 2004) and are likely to move among city greenspaces (Gardiner et al. 2014). Especially for sticky cards, which some arthropods are attracted to (Chen et al. 2015), there is a high probability of overlap between the habitat types. Spiders were sampled by vacuum, and significant differences were found between habitat types in both years, although they were more abundant in bio-cells in 2016 and ornamental landscapes in 2017. Spiders were also found more frequently at the higher collection height. This is most likely because spiders benefit from taller vegetation height and structure for web construction (Gibson et al. 1992)

Epigeal predators and detritivores were similar in abundance between site types. Urban landscapes are highly regulated, with regular mowing, pruning and mulching, and many management strategies decrease habitat complexity, which has been reported to negatively affect natural enemies and detritivores (Langellotto and Denno 2004, Ossola et al. 2016). Both bio-cells and ornamental landscapes have a thick mulch layer which provides habitat and resources for ground-dwelling arthropods. Although mulch thickness was not quantitatively measured, pre-season visual assessments (See Appendix A) showed relatively similar ground cover across all sites. Although leaves and other detritus are commonly removed in urban landscapes, the presence of detritivores and epigeal predators, especially isopods and spiders, can still provide many benefits to the habitat including biological control and food for local birds (Langellotto and Denno 2004, Ladin et al 2015). Based on the composition of the arthropod communities in both the bio-cells and ornamental landscapes the mulch layer may provide enough habitat to support urban epigeal arthropods and detritivores. We did not sample during the winter, but the prominence of bunch grasses and shrubbery in bio-cells may make them valuable overwintering habitat which could support natural enemies as well as ornamental landscapes (MacLeod et al. 2004).

Overall, we also found that bio-cells support similar abundances of aerial, foliar, and epigeal natural enemies and detritivores as ornamental landscapes. Thus, bio-cells, particularly those with high diversity in plant species, contribute to arthropod conservation and potentially to biological control services in urban landscapes. We would suggest that more research is needed to determine which species of plants would support greater diversity of arthropods within bio-cells. Bio-cells are designed for water filtration and many recommendations of suitable plants for urban greenspaces and native landscaping are available that provide pollution filtration and bioaccumulation (Dehnen-Schmutz 2011, Riley and Kraus 2016). These individual plant species could be evaluated by future research to determine which beneficial arthropods they attract, so multifunctional species can be incorporated into bio-cells, but they have yet to be tested for habitat and resource suitability. As bio-cells become more common, it will be easier to assess how different design components such as size, plant diversity, ground cover, and media choice contribute to arthropod abundance diversity in urban landscapes. This study has shown that greater plant diversity supports higher natural enemy abundance and that bio-cells are able to support many of the same arthropod taxa already found in ornamental plantings in urban environments.

Table 1: Biocell and Landscape Area, Plant Species Diversity, and Sampling Dates. Sticky trap samples were collected monthly from May-September in 2016 and from March-July in 2017 at 0.5 m and 1 m heights. Pitfall samples were collected March-August in 2017. Vacuum samples were collected June-August in 2016 and April-July in 2017.

Site	Type	Area (m2)	Plant Species	Number of Samples in 2016		Number of Samples in 2017		
				Sticky trap	Vacuum	Sticky trap	Pitfall	Vacuum
Hunt	Bio-cell	457	8	5	3	5	7	4
Goldenleaf	Bio-cell	265	11	5	2	5	7	4
Talley II	Bio-cell	184	4	5	3	5	7	4
SAS	Bio-cell	177	7	5	3	5	6	4
Steamplant	Bio-cell	127	6	5	3	5	7	4
Talley I	Bio-cell	66	6	5	3	5	7	4
Motorpool	Bio-cell	57	5	5	3	5	7	4
Alliance Deck	Bio-cell	56	2	5	3	5	7	4
Sullivan	Bio-cell	48	7	5	2	5	7	4
Schuab	Bio-cell	43	6	5	3	5	7	4
Hunt Landscape	Landscape	451	8	5	3	5	6	4
Wolfridge	Landscape	262	9	5	3	5	7	4
Flags	Landscape	183	5	5	3	5	6	4
Visitor Center	Landscape	175	7	5	3	5	7	4
Yarborough	Landscape	123	6	5	3	5	7	4
Ligon	Landscape	118	6	5	3	5	7	4
Poulton	Landscape	81	5	5	3	5	7	4
Greek Sign	Landscape	64	4	5	3	5	7	4
Athletics	Landscape	57	8	5	3	5	7	4
Dan Allen	Landscape	52	5	5	3	5	7	4

Figure 1.1: Site locations within Raleigh, North Carolina, USA

Table 2: Significance Tables from Statistical Analysis of Sticky Card Traps. Generalized linear mixed models were used to test the effect of site type, collection height, and number of plant species on insect abundance (collected with yellow sticky cards) in 2016 and 2017.

	2016 Variable	Estimate	*z*	*p*	2017 Variable	Estimate	*z*	*P*
Parasitoid Wasps	Site type	0.093	1.005	0.315	Site type	-0.023	-0.238	0.812
	Collection height	-0.664	-7.170	**<0.001**	Collection height	-0.382	-3.998	**<0.001**
	Plant species	0.054	2.464	**0.014**	Plant species	0.004	0.253	0.863
Predators	Site type	0.006	0.050	0.960	Site type	-0.050	-0.432	0.666
	Collection height	-0.260	-2.375	**0.018**	Collection height	-0.213	-1.800	0.072
	Plant species	0.059	2.261	**0.024**	Plant species	0.054	1.858	0.063
Hemiptera	Site type	0.405	1.397	0.162	Site type	0.726	2.373	**0.018**
	Collection height	0.464	1.644	0.100	Collection height	0.054	0.168	0.867
	Plant species	0.060	0.824	0.410	Plant species	0.074	0.925	0.356
Diptera	Site type	0.095	0.607	0.544	Site type	-0.247	-1.329	0.184
	Collection height	-0.269	-1.698	0.089	Collection height	-0.229	-1.209	0.227
	Plant species	0.114	3.304	**<0.001**	Plant species	0.079	1.994	**0.046**
Coleoptera	Site type	-0.326	-1.852	0.064	Site type	-0.341	-1.815	0.070
	Collection height	-0.740	-4.129	**<0.001**	Collection height	-0.843	-4.396	**<0.001**
	Plant species	-0.101	-2.106	**0.035**	Plant species	-0.010	-0.179	0.858
Araneae	Site type	0.300	0.940	0.347	Site type	0.559	2.653	**0.008**
	Collection height	0.567	1.741	0.082	Collection height	0.464	2.236	**0.025**
	Plant species	-0.011	-0.129	0.897	Plant species	0.025	0.448	0.654

Table 2 Continued

Other	Site type	-0.040	-0.171	0.865	Site type	0.041	0.146	0.884
	Collection height	0.270	1.138	0.255	Collection height	0.506	1.817	0.069
	Plant species	0.196	3.244	**0.001**	Plant species	0.184	2.585	**0.010**

Explanatory variables include site type (bio-cell, landscape) and collection height (1.5m, 0.5 m), and are relative to the reference categories bio-cell and 0.5m. Number of plant species per site was included as a covariate. Sampling date was included as a random effect. Bold values indicate significant effects.

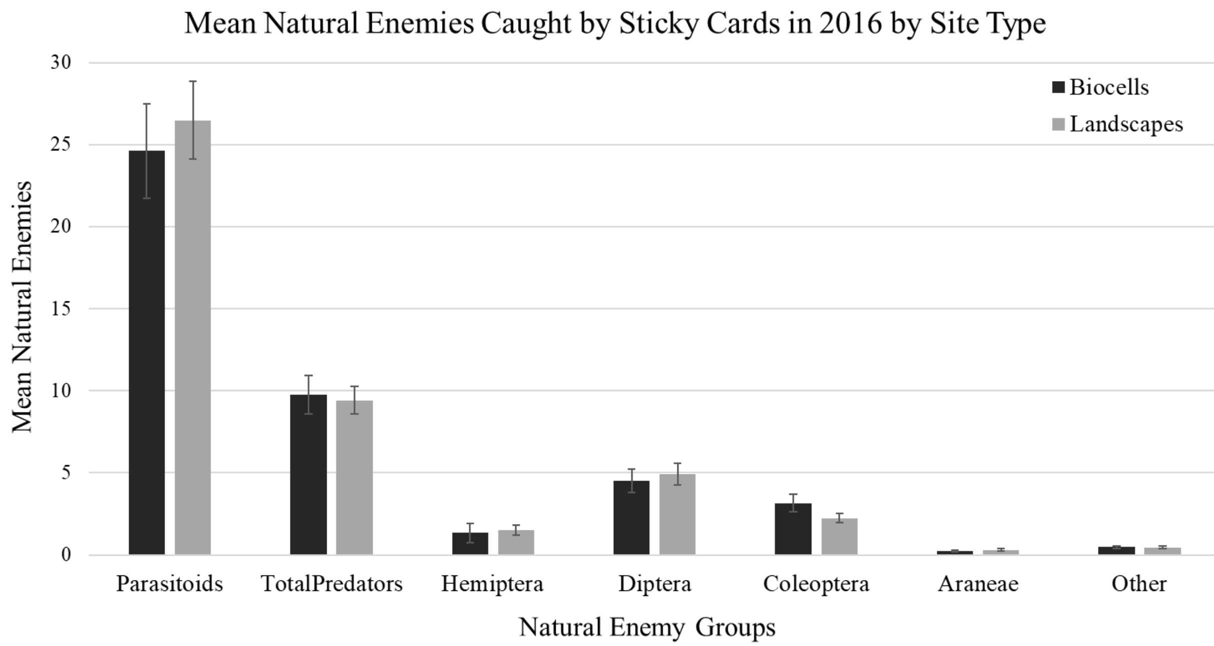

Figure 2.1: Mean natural enemies collected from sticky card traps in 2016.

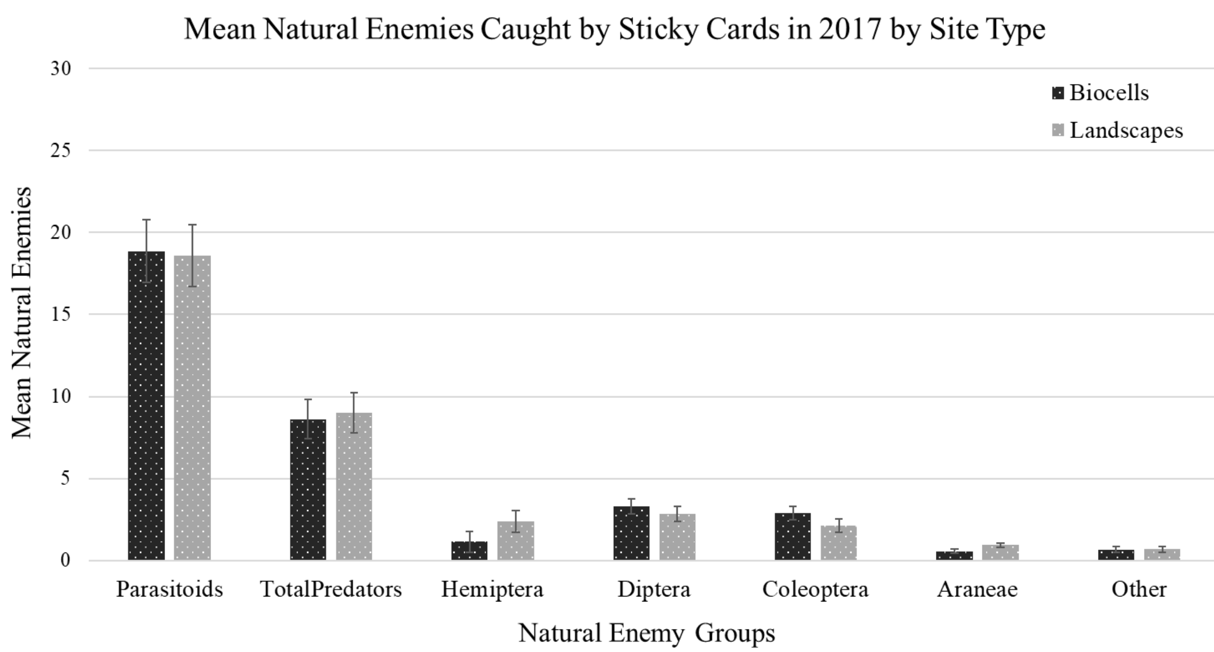

Figure 2.2: Mean natural enemies collected from sticky card traps in 2017.

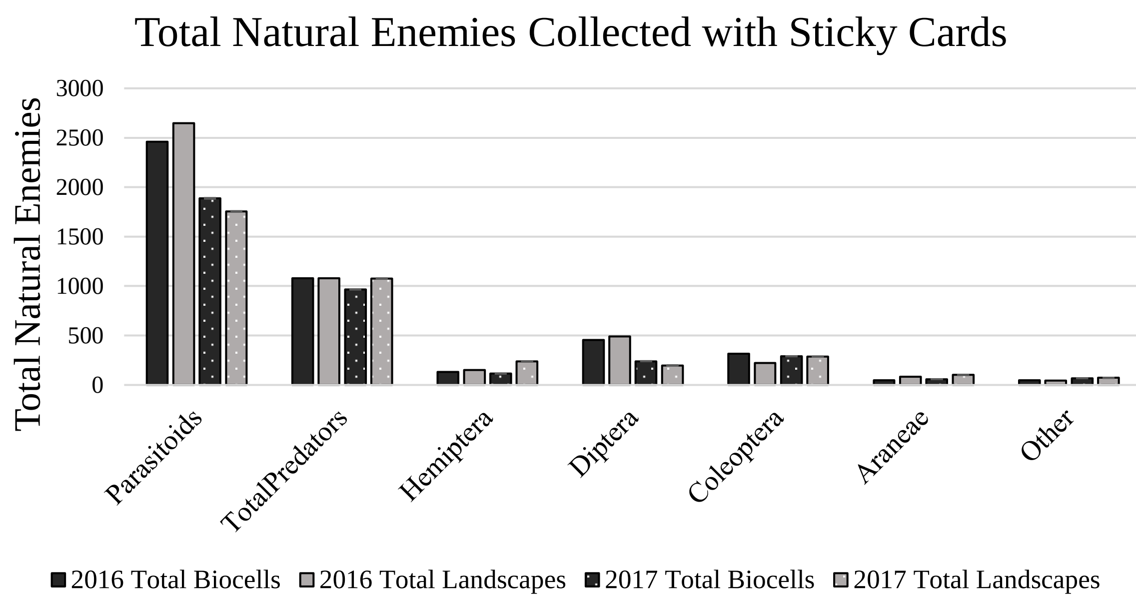

Figure 2.3: Total natural enemies collected from sticky card traps.

Table 3. Significance Tables from Statistical Analysis of Vacuum Samples. Generalized linear mixed models were used to test the effect of site type and number of plant species on insect abundance (collected by vacuum sampling) in 2016 and 2017.

	2016				**2017**			
	Variable	**Estimate**	***z***	***p***	**Variable**	**Estimate**	***z***	***p***
Parasitoid Wasps	Site type	-0.284	-1.019	0.308	Site type	-0.524	-1.837	0.066
	Plant species	-0.056	-0.617	0.537	Plant species	0.199	2.988	**0.003**
Total Predators	Site type	-0.267	-1.139	0.255	Site type	0.394	2.243	**0.025**
	Plant species	-0.052	-0.774	0.439	Plant species	0.039	0.816	0.415
Araneae	Site type	-0.656	-1.968	**0.049**	Site type	0.507	2.360	**0.018**
	Plant species	0.080	0.903	0.366	Plant species	0.064	1.053	0.292
Coleoptera	Site type	-0.236	-0.518	0.604	Site type	0.192	0.394	0.693
	Plant species	-0.096	-0.742	0.458	Plant species	0.146	1.215	0.224
Hemiptera	Site type	2.151	3.134	**0.002**	Site type	-0.086	-0.174	0.862
	Plant species	-0.066	-0.350	0.726	Plant species	0.188	1.601	0.109
Diptera	Site type	-0.556	-0.958	0.338	Site type	-0.090	-0.170	0.865
	Plant species	0.075	0.451	0.652	Plant species	0.160	1.128	0.259
Other	Site type	0.109	0.256	0.798	Site type	0.846	2.284	**0.022**
	Plant species	-0.247	-2.054	**0.040**	Plant species	0.122	1.489	0.136

Explanatory variables include site type (bio-cell, landscape) and are relative to the reference category bio-cell. Number of plant species per site was included as a covariate. Sampling date was included as a random effect. Bold values indicate significant effects.

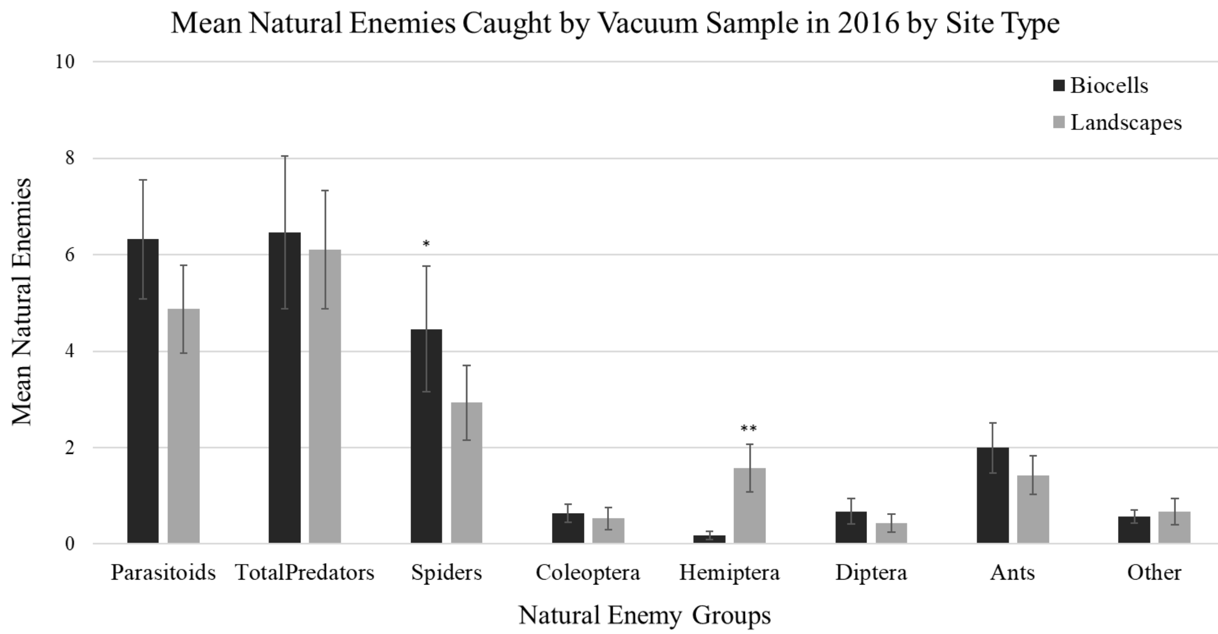

Figure 3.1: Mean natural enemies collected from vacuum sampling in 2016.

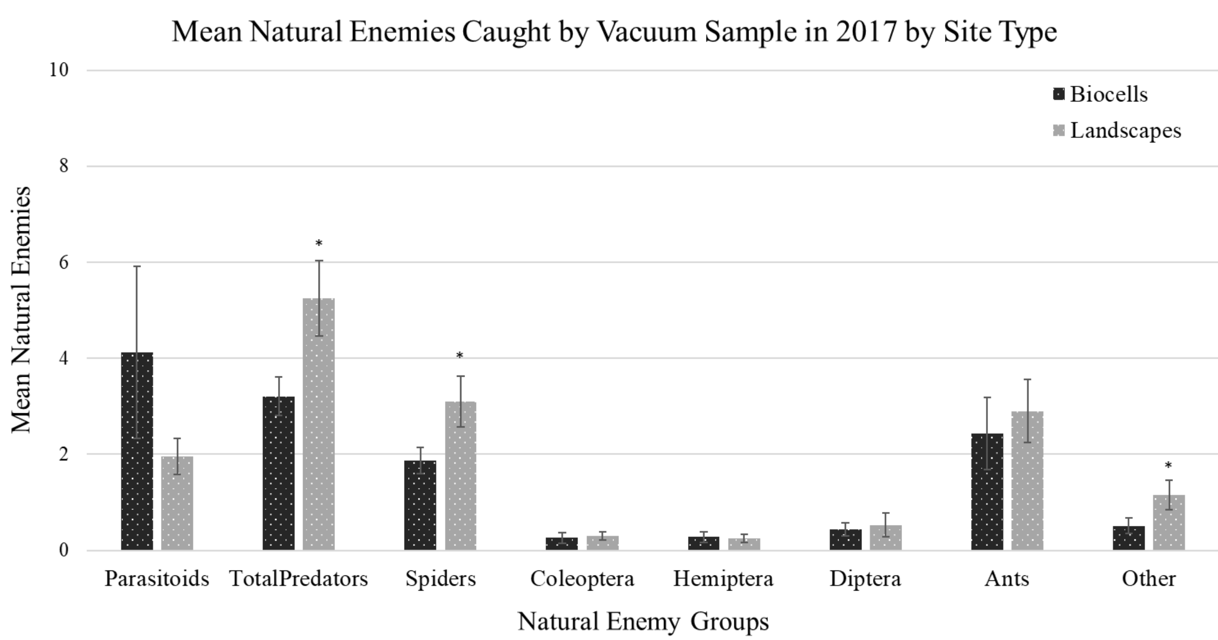

Figure 3.2: Mean natural enemies collected from vacuum sampling in 2017.

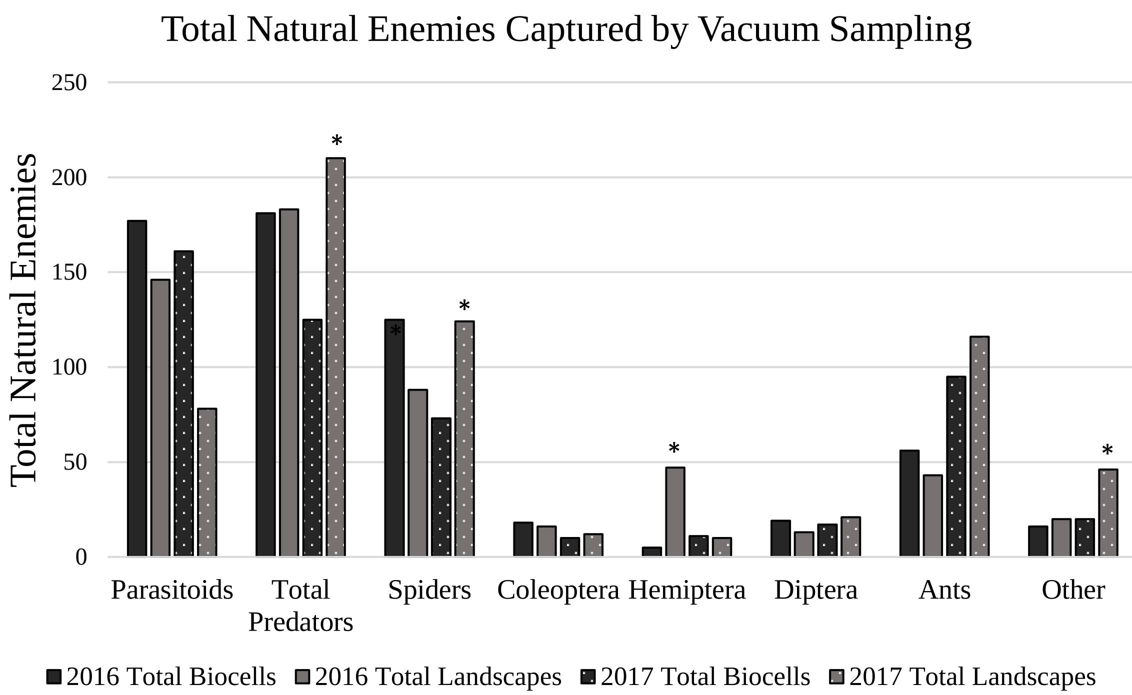

Figure 3.3: Total natural enemies collected from vacuum sampling

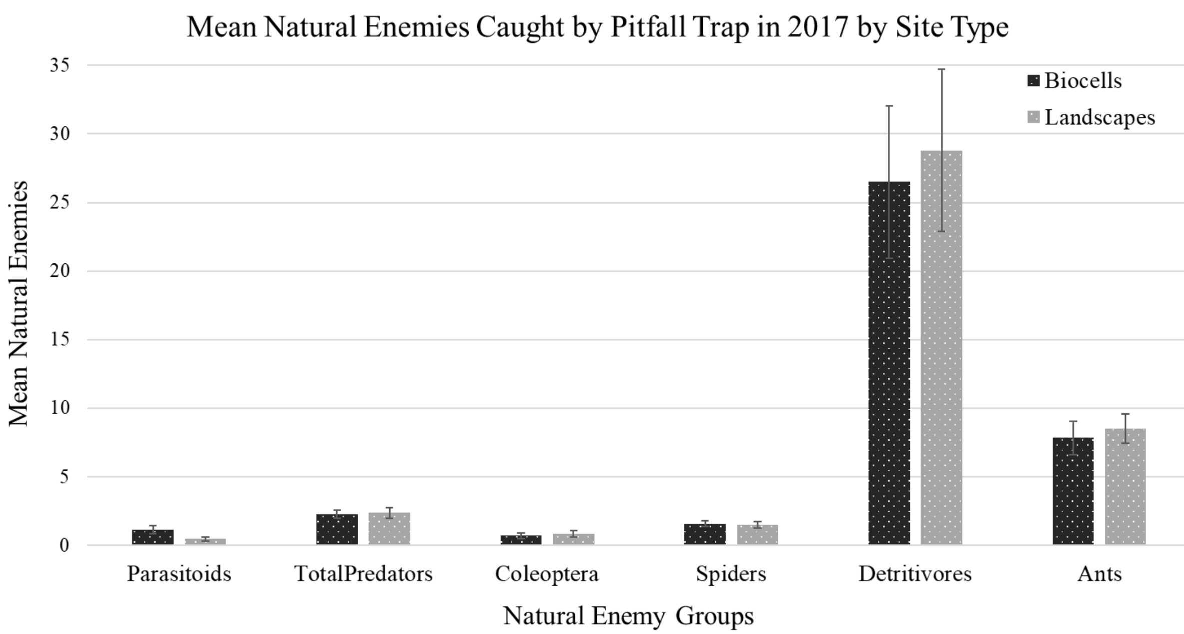

Figure 4.1: Mean natural enemies captured by pitfall traps in 2017

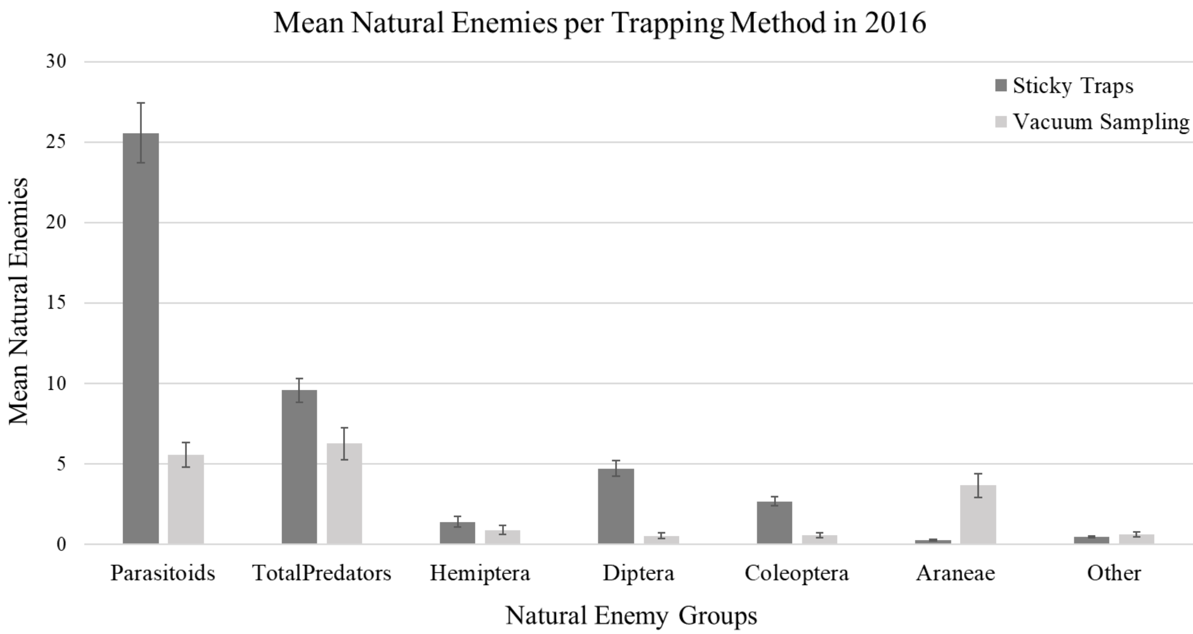

Figure 5.1: Mean natural enemies captured by trap type in 2016

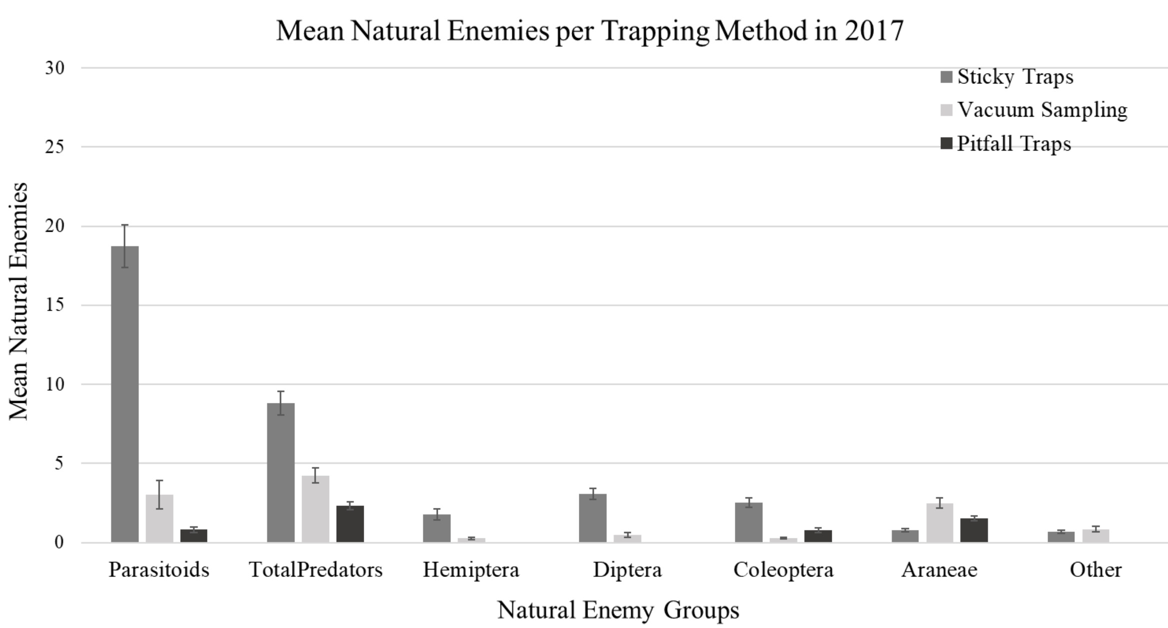

Figure 5.2: Mean natural enemies captured by trap type in 2017

Table 4. Significance Tables from Statistical Analysis of Pitfall Traps. Generalized linear mixed models were used to test the effect of site type and number of plant species on insect abundance (collected by pitfall trap) in 2017.

	Variable	Estimate	*z*	*p*
Parasitoids	Site type	-0.504	-1.194	0.233
	Plant species	-0.026	-0.226	0.821
Predators	Site type	0.041	0.191	0.831
	Plant species	0.033	0.605	0.545
Coleoptera	Site type	0.142	0.408	0.683
	Plant species	-0.208	-1.769	0.077
Araneae	Site type	-0.038	-0.198	0.843
	Plant species	0.092	1.771	0.077
Detritivores	Site type	0.003	0.015	0.988
	Plant species	0.123	1.898	0.058
Formicidae	Site type	0.080	0.431	0.667
	Plant species	0.010	0.181	0.856

Explanatory variables include site type (bio-cell, landscape). Number of plant species per site was included as a covariate. Sampling date was included as a random effect. Bold values indicate significant effects.

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