Variation in Arthropod Communities in Response to Urbanization: Seven Years of Arthropod Monitoring in a Desert City

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Abstract:

Continuous monitoring is essential to understand dynamics of biological communities in response to urbanization, and to provide guidance in landscape planning for conserving urban biodiversity. Arthropods serve this purpose because they are abundant and diverse in urban areas, and relatively easy to collect. Over seven years, in the Central Arizona Phoenix area, arthropod communities in three urban habitat categories were collected and compared to arthropods in natural desert using pitfall traps and non-parametric analyses. First, we tested for differences in arthropod composition, abundances, and diversity across habitats and years. Second, we examined how conclusions about arthropod diversity vary with level of taxonomic resolution. We found that arthropod community composition varied among the four habitats at all taxonomic levels tested. In particular, urban mesic habitats had generally lower diversity than natural desert habitats, although with some exceptions. In contrast, mesic habitats had higher arthropod abundance than all habitats, and fluctuations in abundance were completely independent from changes in precipitation. Taxonomic shortcuts gave overall good impressions of community differences, but finer taxonomic resolutions on certain groups of arthropods revealed distinctly different responses to urbanization (e.g., higher beetle and ant diversity in the urban habitats). Urban areas have great potential for arthropod diversity, but community composition and dynamics are notably different from natural habitats. Institutions, local governments and homeowners can make an impact in arthropod conservation by choice of

landscaping, and we recommend that remnants of natural habitats within cities receive further attention in urban planning.

Graphical Abstract:

Arthropod diversity
Abundance
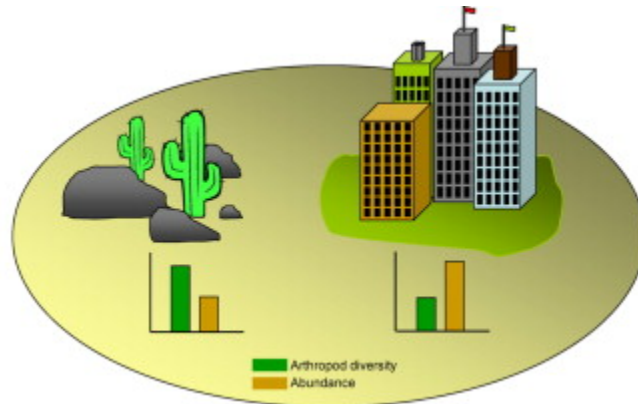
Keywords: Arthropods | Diversity | Monitoring | Precipitation | Remnant | Urbanization

Article:

1. Introduction

Cities represent hotspots of local species extinction, as urbanization often transforms native communities to more homogenous global communities (McKinney, 2006). Although cities account for only 2.8% of the total land area on Earth, urban areas harbor more than half of the world's human population (Grimm et al., 2008,McGranahan et al., 2005 and United Nations, 2008). Sprawling urban areas influence surrounding rural and natural ecosystems by introductions of non-native species, fragmentation of habitats, and alterations of local and regional climates, water and air quality, and biogeochemical cycles (e.g., Grimm et al., 2008). It is essential to understand how these processes affect abundance, diversity and species composition of urban communities because changes in these community attributes may alter the structure and functioning of ecosystems (e.g., Chapin et al., 1997 and Duffy, 2009).

Many studies of urbanization and diversity have focused on birds, arthropods or plants (Faeth, Bang, & Saari, 2011). In general, bird richness decreases in cities (e.g., Chace and Walsh, 2006, Faeth et al., 2011 and McKinney, 2008) whereas plant richness may increase because of human introductions of non-native plant species (e.g., Walker, Grimm, Briggs, Gries, & Dugan, 2009). Arthropods are widely recommended as indicators of the ecological health of terrestrial ecosystems (Kremen et al., 1993). Because of the ubiquity of arthropods in terms of abundances, species richness, and trophic functions (i.e., consumers, detritivores, predators, parasites, pollinators, and vectors of disease), they are ideal for monitoring biodiversity in urban ecosystems (McIntyre, 2000).

Arthropods encompass a range of functional groups, and consequently, results of urban biodiversity studies are often contradictory (Faeth et al., 2011). Some studies have demonstrated that arthropod diversity decreases with urbanization (e.g., Clark, Reed, & Chew, 2007 (butterflies); Sadler, Small, Fiszpan, Telfer, & Niemelä, 2006 (ground beetles)), whereas other studies report the opposite (e.g., Lessard & Buddle, 2005(ants); Rickman & Connor, 2003 (leaf-mining moths)). Still other studies show no effect of urbanization on arthropod diversity (Faeth et al., 2011). The effects of urbanization on arthropod biodiversity may also be more subtle. For example, urbanization may have no effect on richness, but specialist species may be replaced by generalists, and interactions important to community structure may disappear (Deichsel, 2006 (ground and rove beetles)). Declines in diversity may further lead to altered foraging behavior (Thompson & McLachlan, 2007 (ants)). Likewise, changes in abundances of arthropods with urbanization vary widely among studies, ranging from increases to decreases in abundances depending on the taxa of interest (Faeth et al., 2011). Most studies of urbanization effects on arthropod biodiversity are relatively short-term and focus on only one or a few functional or taxonomic groups, which may also account for disparities in results among studies. Long-term studies of arthropods are therefore warranted in urban areas, with a broad focus on different groups.

To describe differences in arthropod communities in response to urbanization, we report seven years of monitoring of arthropods in and surrounding Phoenix, AZ. Four habitat types were compared that comprise the majority (84.7%) of land-use types of the total Phoenix metropolitan area (McIntyre, Rango, Fagan, & Faeth, 2001). Two residential landscape types, mesic and xeric, as well as remnant areas of the Sonoran Desert, were compared with communities of the surrounding desert area. The terms 'habitat' or 'habitat type' refer to areas of similar vegetation or land cover (Miller & Hobbs, 2007). Due to differences in native vs. non-native plants, irrigation regimes (Martin, 2001), and isolation effects due to fragmentation (e.g., Meffe, Carroll, & Contributors, 1997), we expected that the arthropod communities would be different in terms of composition, diversity, evenness and abundance. More specifically, we expected urban arthropod communities to be less diverse, less even, but more abundant than desert communities. These predictions were based on earlier studies describing strong effects of land-use change on arthropod communities (e.g.,Cook and Faeth, 2006, McIntyre et al., 2001 and Rango, 2005).

Cities often have limited budgets for landscape and biological conservation. For this reason, it is imperative that diversity assessments are cost- and time efficient if they are to have any impact on political decisions and planning. We therefore evaluated our data at different taxonomic resolutions, to determine if taxonomic shortcuts can be used to assess the effects of urbanization, specifically land-use change, on arthropod abundances and diversity.

2. Methods

2.1. Study area

The Phoenix metropolitan area is located in the northern part of the Sonoran Desert, AZ, USA, where the Central Arizona Phoenix Long-Term Ecological Research (CAP LTER) program has been monitoring the urban ecosystem on different spatial and temporal scales since 1998 (Grimm & Redman, 2004). The urban area is a patchwork of different types of residential landscapes, commercial land, parks, industrial and agricultural fields as well as patches of natural vegetation. Residential areas in this water-limited city consist of different landscape types, depending on social economy, age of neighborhood and homeowner's associations (Hope et al., 2003). Ground-dwelling arthropods have been sampled annually via pitfall traps, covering a spatial extent of 5200 km^2. Studies have been published from the earlier years of this long-term monitoring database, covering many taxonomic groups (Cook and Faeth, 2006 and McIntyre et al., 2001) or certain groups (Shochat, Stefanov, Whitehouse, & Faeth, 2004). In 2002, the monitoring project changed sampling locations, although within the same landscape categories. Thus, this paper is the first to report sampling results from 2002 to 2008. We include only locations that were sampled continuously throughout the study (Fig. 1). Here we focus on four of the dominant habitat types, including desert sites ($n = 7$), desert remnant sites ($n = 3$), xeric yards ($n = 2$) and mesic yards ($n = 4$). To compare with arthropods living in vegetation, we included sweep-net samples from 131 localities sampled in 2005, including desert sites ($n = 56$), desert remnant sites ($n = 12$), xeric yards ($n = 30$) and mesic yards ($n = 33$).
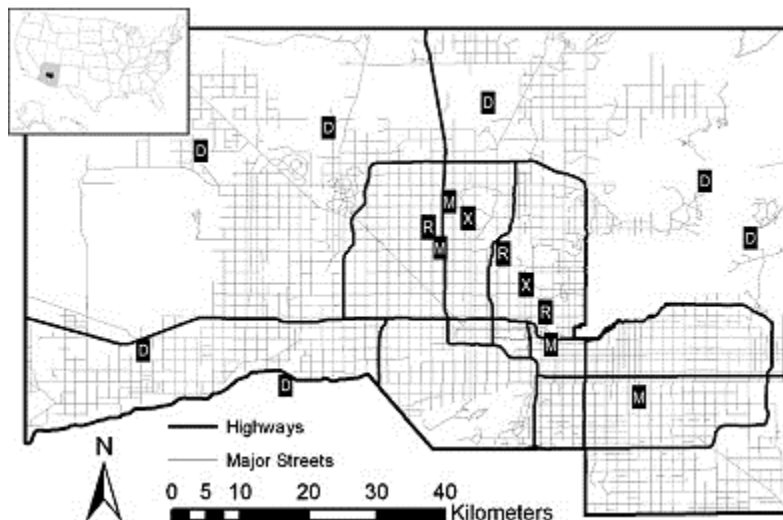
Fig. 1. Map of pitfall trap locations; (D) desert, (R) desert remnant, (X) xeric yard, (M) mesic yard. The 131 locations for sweep-net samples roughly cover the whole mapped area and are not shown.

The selected habitats have different vegetation characteristics that might potentially influence the arthropod communities. Desert habitats contain vegetation typical for the Sonoran Desert, are contiguous with the Sonoran Desert as a whole, and are located far from residential neighborhoods. The desert remnant sites in this study (hereafter termed remnants) are once-natural desert areas completely surrounded by urban development, where effects of human

activity are evident. Most of the plants are native, but some non-native plants may be found. Between 1995 and 1998, the expansion of the urban fringe in parts of Phoenix occurred at a rate of one mile per year (Gober & Burns, 2002), thereby decreasing the immigration rate of species as these urban islands became increasingly isolated. In addition, urban development increased at the core of the metropolitan region (Waits, 2000). Xeric yards contain low-water-use plants, but not necessarily native species (in our two xeric yards, the dominant plant was the native *Larrea tridentata*). The plants may be on drip irrigation, but the ground surface consists of decomposing granite instead of lawn (Martin, 2001). Mesic yards have many exotic plant species, green lawns, large trees and palms, and are heavily watered, either by flood irrigation or sprinklers (Martin & Stabler, 2002). The dominant plants in the mesic yards were non-native plants such as *Citrus sinensis*, *Hibiscus* sp., *Lantana* sp., *Tecomaria capensis*, *Malva parviflora*, and natives such as *Prosopis velutina*, *Pseudorontium cyathiferum* and *Phacelia affinis*, and usually extensive turf grass cover.

2.2. Sampling, identification and data mining

Ground arthropods were sampled according to protocol at the CAP LTER website (http://caplter.asu.edu/data/protocols/?id=22) in 16 sites two to nine times per year. At each site arthropods were collected on transects of 10 traps each, with each trap consisting of an un-baited 500-ml plastic cup (P-16 plastic Solo cups with lids) set just below the surface. Traps were left open for three days. For quantitative comparisons we standardized the arthropod abundances by adjusting for number of visits and missing traps. Each annual sample was divided by number of trap samples per habitat, and then multiplied by 150. Empty pitfall traps were included as zero-samples. For diversity and similarity indices we used unadjusted raw and transformed raw data, respectively.

Pitfall sampling is one of the easiest and least expensive methods for collecting large numbers of arthropods (Ausden & Drake, 2006). This method, however, is biased towards ground-dwelling, mobile arthropods, a group in which many of the taxa are difficult to identify. A frequently used taxonomic shortcut is to identify all taxa as detailed as possible, occasionally termed "taxonomic sufficiency" (Ellis, 1985) or "lowest practical taxonomic level" (LPT) (e.g., Hanula, Wade, O'Brien, & Loeb, 2009). This method allows the estimate of general feeding preferences based on literature and web searches, depending on taxonomic resolution. Since analyses at this level of resolution in theory are based on comparing incommensurable taxa (Krell, 2004), multivariate statistical analyses should ideally be performed at a similar taxonomic level, for example family. Here, we analyzed the arthropods at several taxonomic resolutions to assess the diversity in the selected habitats.

The arthropods were sorted to morphologically similar groups, and identified to LPT level by CAP LTER personnel, using a reference collection and appropriate keys. In 2005–2006 the identification protocol was changed for Collembola and Formicidae, identifying them to lower taxonomic levels (increasing resolution). This could lead to an increase in potential taxon

richness, and the results and discussion are treated accordingly. Sample data were entered in the CAP LTER database (publicly available), and queries were run to extract data for the habitats and time periods that we evaluated. We excluded specimens from groups whose primary means of locomotion is flight (e.g., Diptera, Lepidoptera, Neuroptera, Trichoptera and winged Hymenoptera), as pitfall trapping is inappropriate for sampling these groups (Ausden & Drake, 2006). Where possible, we assigned each taxonomic unit to a feeding guild based on literature and web searches (e.g.,Bartlett, 2005 and Borror et al., 1989). Some of these guild designations may not be completely accurate, but the goal was a coarse estimate of feeding-guild abundances. A complete list of taxa and their guilds is included in Appendix A and Appendix B.

A complementary sampling campaign was done in 2005 using sweep nets on vegetation-living arthropods in 131 similar locations, of which 13 locations overlap with the pitfall locations. Samples were taken from the dominant woody vegetation by shaking three branches into the sweep net, and collecting arthropods in jars containing 70% ethanol (http://caplter.asu.edu/data/protocols/?id=1 andhttp://caplter.asu.edu/data/protocols/?id=84). These were identified as for the pitfall samples, and are listed in Appendix A and Appendix B. All specimens are stored in the School of Life Sciences A-building at Arizona State University, Tempe.

Initially, we compared all sites at LPT level to see if our habitat categories could be justified based on community composition. We further did analyses on LPT level, order level, family level, spider and beetle families, and ultimately we analyzed families where more than 30% of the specimens were identified to genus.

2.3. Diversity, similarity and precipitation

We used Fisher's α (Fisher, Corbet, & Williams, 1943) as measure of arthropod diversity. This index allows us to compare communities with different sizes and sampling effort, and can be interpreted as the approximate number of species (taxa) represented by a single individual (Magurran, 2004). Fisher's α was calculated using EstimateS (Colwell, 2006) with 500 randomizations and analytical standard deviations. For a visual comparison of annual variation of the pitfall samples, we used Non-metric multidimensional scaling (NMS). To test the significance of these patterns, we used Non-Parametric Multivariate Analysis of Variance, NPMANOVA (Anderson, 2001) on $\log_{10}[n + 1]$-transformed data. For these procedures we used PAST ver. 1.93 (Hammer, Harper, & Ryan, 2001). Both of these procedures were performed using Morisita distance. This is a similarity measure recommended for comparing habitats with different sampling effort (Magurran, 2004). Evenness was assessed by regressing the $\log_{10}[n + 1]$-transformed adjusted rank-abundance curves against the log rank, where a steeper slope means lower evenness in arthropod distribution (maximum evenness = 0). This method is useful since it can be tested statistically with analysis of covariance (ANCOVA). For this method, we used PROC REG and PROC GLM with Tukey–Kramer adjusted P-values for post hoc tests using SAS Software, version 9.2 (SAS Institute, Cary, NC, USA).

Water is the key limiting resource in deserts, potentially influencing all trophic levels (Noy-Meir, 1974), so we chose precipitation as a key variable that may explain fluctuations in abundance. There is also a strong foundation for this relationship in the literature for many other habitats (Begon, Harper, & Townsend, 1996). Precipitation data from Sky Harbor Phoenix airport were provided by National Climatic Data Center (NCDC). These data characterize precipitation in the Phoenix area fairly well (Goodrich, 2005) and were used for main habitat arthropod fluctuations. Since there is normally a certain time lag for arthropods to respond to precipitation pulses in arid environments (Sears, Holt, & Polis, 2004), we combined the summer rain and fall rain from the previous year with the winter rain. For example, the total rainfall from July 2003 to March 2004 would likely influence abundance of arthropods in 2004. Relationships between log$e$-transformed abundance and annual precipitation were thus tested using simple linear regression at a 0.05 significance level using R, version 2.10.1 (R Development Core Team, 2010).

3. Results

A total of 238,769 arthropods were identified to 284 taxa from the pitfall sampling, and 2969 arthropods were identified to 93 taxa from the sweep-net sampling in 2005 (Appendix A and Appendix B). By excluding taxa that were only identified to subclass (Acari, Chilopoda, and some Collembola), the dataset was reduced to 94,416 specimens spread across 29 orders. Excluding taxa only identified to subclass, order and superfamily left 79,170 specimens spread across 93 families. The sweepnet samples were identified to 76 families (2965 specimens). The results for analyses at each taxonomic level in different habitats are summarized in Table 1.

Table 1. Summary of major community characteristics at different taxonomic resolutions from 2002 to 2008. See text for details.

Taxonomic resolution	Group	Composition	Diversity	Evenness	Abundance	Abundance vs. precipitation
Order	All	Desert is separated from mesic and closest to remnant; xeric is closest to mesic	Desert is highest	No differences	Mesic is highest	No correlation
Family	All	Desert is separated from mesic and closest to remnant; xeric is closest to mesic	Desert is highest	Remnant most even, mesic least	Mesic is highest	No correlation
	Spiders	Mesic different from all other habitats	Remnant is highest, mesic is lowest	Remnant most even, xeric least	Mesic is highest, remnant is lowest	Positive correlation in xeric

	Beetles	Mesic different from all other habitats	Mesic is highest, remnant is lowest	Desert most even, remnant least	Mesic is highest, xeric is lowest	No correlation
Genus	Tenebrionidae	Desert is separated from mesic and closest to remnant; xeric is closest to mesic	Desert is highest	Not tested	Remnant is highest, mesic is lowest	No correlation
	Formicidae	Mesic separated from both desert and remnant habitats	Mesic is highest, remnant is lowest	Not tested	Mesic is highest, xeric is lowest	No correlation
LPT	All	Desert is separated from mesic and closest to remnant; xeric is closest to mesic	Desert is highest	Desert most even, xeric least	Mesic is highest	Positive correlation in remnant and xeric
LPT	*Sweep-net samples 2005*	Not tested	Mesic is highest, remnant is lowest	Not tested	Not tested	Not applicable
Family	*Sweep-net samples 2005*	Not tested	Desert is highest, remnant is lowest	Not tested	Not tested	Not applicable

3.1. Comparing communities at lowest practical taxonomic (LPT) level

We first tested if the chosen sites could be grouped into general habitat categories based on arthropod composition. Annual site samples were ordinated and compared at LPT level. The habitat groups were significantly different (NPMANOVA, $F = 7.629$, $P < 0.0001$, Morisita distance, $\log_{10}[n + 1]$-transformed) indicating that our categorization of habitats is reasonable. The first ordination of the communities revealed two distinct groups: samples from 2002 to 2005 and samples from 2006 to 2008 (not shown). To further dissect these two clusters, we analyzed each separately (Fig. 2). Both of these ordinations separated desert sites from mesic sites, with xeric and remnant sites falling somewhere in between these sites (Table 1). The habitats were significantly different (NPMANOVA, $F = 9.704$, $P < 0.0001$, and $F = 10.41$, $P < 0.0001$, 2002–2005 and 2006–2008, respectively).
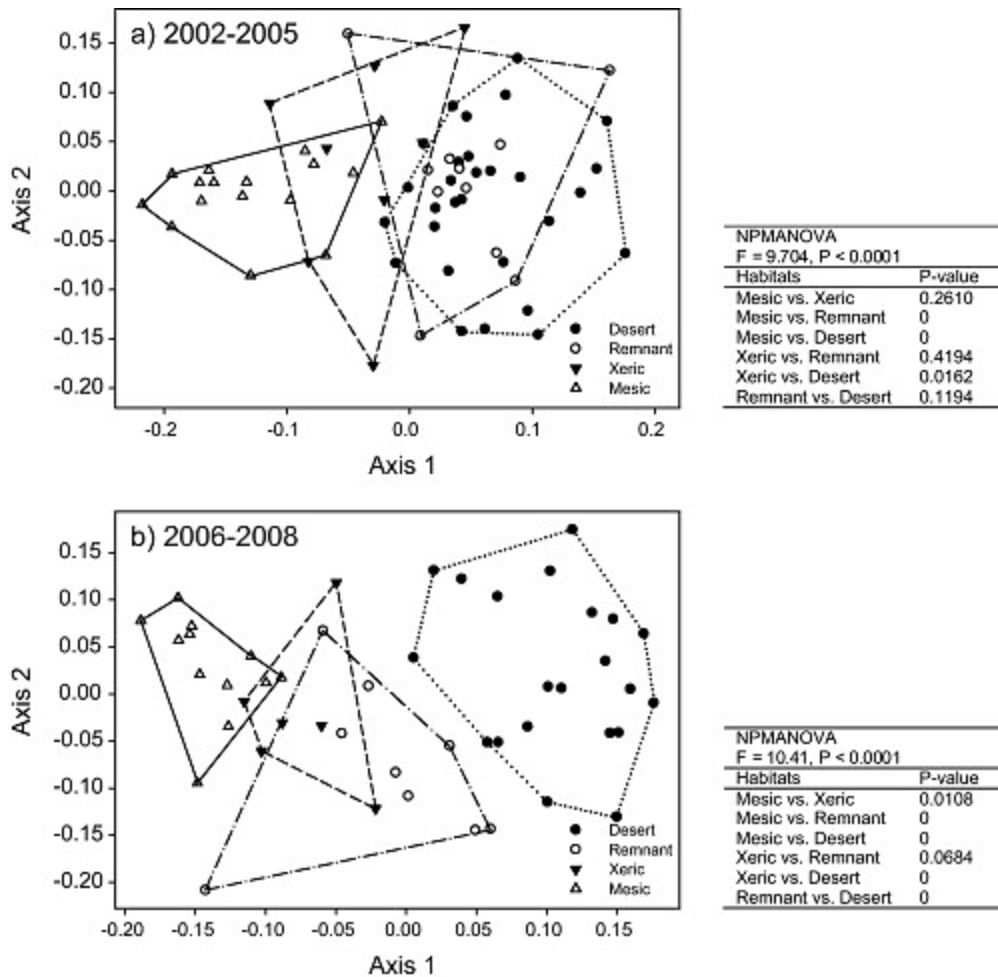
Fig. 2. Non-metric multidimensional scaling of annual pitfall samples, $\log_{10}[n + 1]$-transformed abundances, lowest practical taxonomic level. (a) Sites 2002–2005 (stress 0.2264, Axis 1: 49.35%, Axis 2: 20.86%). (b) Sites 2006–2008 (stress 0.2231, Axis 1: 52.1%, Axis 2: 20.16%). P-values are Bonferroni corrected. One dot represents the arthropod composition in one location one year. The closer the dots are together, the more similar is the arthropod composition.

As the sites properly constitute different habitat types based upon arthropod assemblages, all further analyses were done with pooled sites into four distinct habitat categories. This produced a similar, and still significant, but clearer result (NPMANOVA, $F = 3.417$, $P = 0.0036$, not shown). Mesic habitats were still significantly different from desert ($P = 0.0342$) and remnant ($P = 0.0426$), but not from xeric ($P = 0.7068$). Desert habitats had overall the highest diversity, with more variation among the other three habitats.

Arthropods were most abundant in the mesic habitat, with desert, xeric and remnant alternating between having the lowest abundance (Fig. 3). Abundance of arthropods was positively correlated with previous summer and winter precipitation in remnant and xeric habitats (simple

linear regression, log$e$-transformed abundance, $F_{1,5} = 8.590$, $R^2 = 0.632$, $P = 0.0326$ (remnant), and $F_{1,5} = 7.374$, $R^2 = 0.596$, $P = 0.0420$ (xeric), Fig. 3). The relationship was not significant in the two other habitats ($F_{1,5} = 0.579$, $R^2 = 0.104$, $P = 0.4809$ (desert), and $F_{1,5} = 0.009$, $R^2 = 0.002$, $P = 0.9272$ (mesic)).
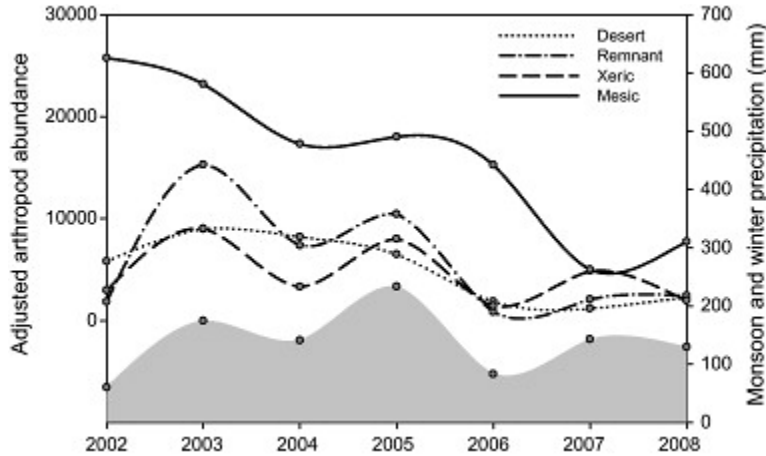
Fig. 3. Changes in arthropod abundance (lowest practical taxonomic level, left axis) from 2002 to 2008 with annual precipitation (previous year's summer and winter, shaded area, right axis). Abundance in remnant and xeric habitats were significantly correlated with precipitation (see text). The curves are smoothed (cubic spline). Gray dots indicate original data points.

Analysis of covariance on the slopes of $\log_{10}[n + 1]$-transformed ranks revealed significant differences in evenness for both time intervals (ANCOVA, $F_{1,3} = 31.16$, $P < 0.0001$, 2002–2005), with mesic habitats being significantly less even than all the other habitats ($\beta_1 = -2.561$ for the mesic habitat vs. $\beta_1 = -2.311$ (desert), $\beta_1 = -2.163$ (remnant) and $\beta_1 = -2.065$ (xeric), $P < 0.0001$, Tukey–Kramer adjusted P-values). The pattern was similar from 2006 to 2008 where the evenness was significantly different (ANCOVA, $F_{1,3} = 28.55$, $P < 0.0001$), and all the slopes were significantly different from each other ($\beta_1 = -1.907$ (desert), $\beta_1 = -2.215$ (mesic), $\beta_1 = -1.877$ (remnant) and $\beta_1 = -1.911$ (xeric), $P < 0.0001$, Tukey–Kramer adjusted P-values).

The sweep-net samples from 2005 revealed that the mesic habitat had the highest diversity of vegetation-living arthropods, followed by desert, xeric and remnant habitats (Table 2). Although not directly comparable due to difference in number of sampling sites and methods, pitfall data for the same year showed that desert habitats were most diverse and xeric habitat the least. Mesic and remnant habitats were intermediate.

Table 2. Diversity of arthropods at three taxonomic levels in four habitat categories from 2002 to 2008.

Year	Desert	Remnant	Xeric	Mesic

Taxonomic level: LPT			
2002	6.80 ± 0.34	7.67 ± 0.48	4.36 ± 0.37	5.89 ± 0.28
2003	7.96 ± 0.33	7.12 ± 0.34	7.72 ± 0.41	5.46 ± 0.26
2004	11.89 ± 0.45	11.54 ± 0.51	11.17 ± 0.63	8.52 ± 0.35
2005	12.96 ± 0.53	9.5 ± 0.45	8.18 ± 0.45	10.45 ± 0.42
2005[a]	11.90 ± 0.73	10.39 ± 1.08	11.53 ± 1.03	12.62 ± 0.95
2006	19.78 ± 0.88	12.97 ± 1.02	12.78 ± 0.97	13.46 ± 0.51
2007	21.95 ± 1.07	13.27 ± 0.78	6.49 ± 0.44	14.80 ± 0.67
2008	17.57 ± 0.83	12.4 ± 0.77	9.45 ± 0.75	10.81 ± 0.53
Taxonomic level: order			
2002	2.30 ± 0.20	2.73 ± 0.26	2.70 ± 0.32	1.80 ± 0.16
2003	2.22 ± 0.16	2.38 ± 0.20	2.29 ± 0.23	1.58 ± 0.15
2004	2.43 ± 0.19	2.61 ± 0.21	2.82 ± 0.28	1.66 ± 0.14
2005	2.92 ± 0.24	2.62 ± 0.24	2.59 ± 0.28	1.95 ± 0.17
2006	3.00 ± 0.24	2.65 ± 0.31	2.36 ± 0.28	1.86 ± 0.15
2007	2.88 ± 0.25	2.49 ± 0.24	2.00 ± 0.20	2.51 ± 0.21
2008	2.92 ± 0.24	3.52 ± 0.33	2.30 ± 0.27	2.21 ± 0.18
Taxonomic level: family			
2002	5.58 ± 0.36	5.88 ± 0.47	3.00 ± 0.36	6.17 ± 0.40
2003	6.29 ± 0.34	5.45 ± 0.35	7.13 ± 0.53	5.39 ± 0.34
2004	5.95 ± 0.34	6.29 ± 0.39	6.08 ± 0.50	5.59 ± 0.34
2005	6.95 ± 0.45	5.62 ± 0.42	5.57 ± 0.50	7.04 ± 0.44
2005[a]	10.63 ± 0.68	8.40 ± 0.90	10.42 ± 0.95	10.10 ± 0.80
2006	5.68 ± 0.37	4.46 ± 0.47	5.38 ± 0.55	4.75 ± 0.28

| 2007 | 6.41 ± 0.44 | 5.09 ± 0.40 | 2.52 ± 0.23 | 6.10 ± 0.40 |
| 2008 | 7.60 ± 0.48 | 4.70 ± 0.42 | 4.01 ± 0.42 | 4.98 ± 0.32 |

Notes: Fisher's α ± analytical standard deviation. These measures should be compared within year, not between years. [a]Sweep-net samples.

For the LPT level summed up for all seven years, 24% of the taxa were found in all four habitat types (Appendix A and Appendix B). The desert habitat had 19% unique taxa, where the most prominent taxa were the ant *Aphaenogaster cockerelli*, lygaeid bugs from the genus *Neacoryphus* and ants from the genus *Messor*. 17% of the taxa were only found in the mesic habitat, with the wolf spider genera *Pardosa* and *Allocosa* as prominent taxa. Remnant habitats contained 4% taxa that were unique, but the most abundant of these had only two individuals. 5% of the taxa were unique to xeric habitats, but these were also in very low numbers (<5 individuals). 8% of the taxa were found exclusively in desert and remnant areas, where the harvester ant genus *Pogonomyrmex* and the bristletail family Meinertellidae were most abundant. In general, most granivorous ants were found in highest abundances in the desert habitat. Xeric habitats had more taxa similar to desert than to mesic habitats.

3.2. Comparing communities at the order level

The different identification protocols only moderately affected the continuity at the order level, thus these were analyzed for the entire period 2002–2008. The communities remained significantly different at this taxonomic level (NPMANOVA, $F = 4.612$, $P = 0.0027$, Morisita distance, $\log_{10}[n + 1]$-transformed), and mesic habitats were significantly different from desert and remnant habitats. Ordination of the results revealed a similar pattern as seen for the LPT level, albeit on a coarser resolution (Fig. 4). Desert and mesic communities were very different in composition of orders, and also clearly separated in terms of diversity, with desert communities repeatedly being significantly more diverse than mesic communities (Table 2). Mesic communities were still far more abundant than in the other three habitat categories. The fluctuation in abundance could not be explained by fluctuations in summer and winter precipitation in any of the habitats ($F_{1, 5} = 0.1275$, $R^2 = 0.025$, $P = 0.7356$ (desert); $F_{1, 5} = 4.2930$, $R^2 = 0.462$, $P = 0.0930$ (remnant); $F_{1, 5} = 0.9913$, $R^2 = 0.166$, $P = 0.3651$ (xeric), and $F_{1, 5} = 1.8410$, $R^2 = 0.269$, $P = 0.2328$ (mesic)). Analysis of covariance on the slopes of $\log_{10}[n + 1]$-transformed ranks did not reveal any significant difference in evenness (ANCOVA, $F_{1, 3} = 2.18$, $P = 0.0963$). The slopes were not significantly different, although desert and remnant had slightly higher evenness (desert $\beta_1 = -1.177$, remnant $\beta_1 = -1.171$, xeric $\beta_1 = -1.309$ and mesic $\beta_1 = -1.394$). Sweep-net samples resulted in only ten orders (Appendix A and Appendix B), and were not included in the order analysis.

Fig. 4. Non-metric multidimensional scaling of annual pitfall samples, habitats and $\log_{10}[n + 1]$-transformed abundances at order level (stress 0.1099, Axis 1: 77.46%, Axis 2: 11.86%). *P*-values are Bonferroni corrected.

3.3. Comparing communities at the family level

Number of families was only moderately affected by the change in identification protocol. The four habitats differed significantly in community composition (NPMANOVA, $F = 6.484$, $P < 0.0001$, Morisita distance, $\log_{10}[n + 1]$-transformed), with mesic habitats significantly different from all the other habitats. Community composition at the family level was very similar to the observed pattern at LPT level, separating mesic from desert habitats, but with remnant and xeric habitats intermediate (Fig. 5). On average, desert habitats had higher family diversity, while diversity in the xeric habitat varied the most over seven years (Table 2). Patterns in abundance at the family level were not very different from those at the order level, and similarly, the family abundance was not significantly correlated with previous summer and winter precipitation in any of the habitats ($F_{1,5} = 0.0131$, $R^2 = 0.003$, $P = 0.9134$ (desert); $F_{1,5} = 5.2120$, $R^2 = 0.510$, $P = 0.0713$ (remnant); $F_{1,5} = 0.6748$, $R^2 = 0.119$, $P = 0.4498$ (xeric); and $F_{1,5} = 1.8880$, $R^2 = 0.274$, $P = 0.2278$ (mesic); data not shown). Analysis of covariance on the slopes of log-transformed ranks revealed that evenness varied significantly among habitat types (ANCOVA, $F_{1,3} = 15.13$, $P < 0.0001$), although no significant differences were found comparing the individual slopes (desert $\beta_1 = -2.287$ vs. mesic $\beta_1 = -2.765$, $P = 0.0921$; desert vs. remnant $\beta_1 = -2.257$, $P = 0.8558$, desert vs. xeric $\beta_1 = -2.281$ $P = 0.9958$; mesic vs. remnant $P = 0.4287$; mesic vs. xeric, $P = 0.0674$; and remnant vs. xeric, $P = 0.7551$, Tukey–Kramer adjusted *P*-values).
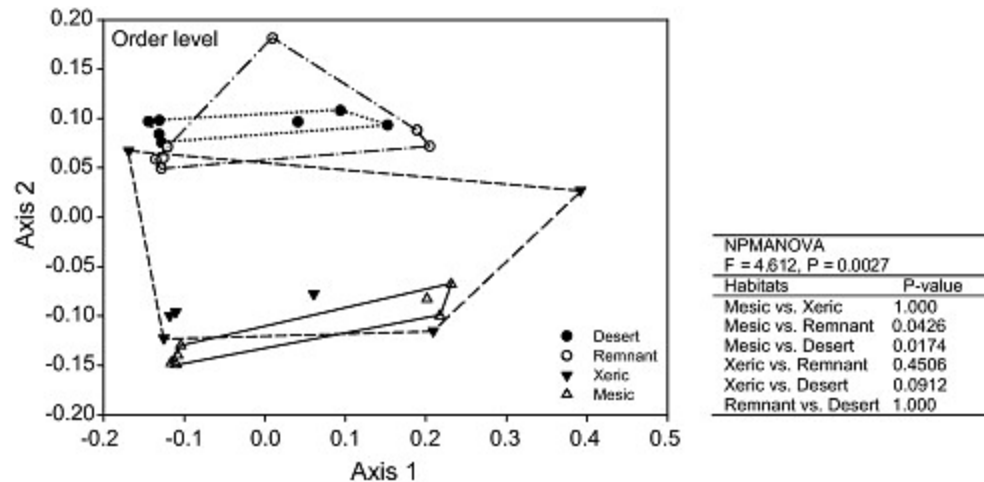
Fig. 5. Non-metric multidimensional scaling of annual pitfall samples, habitats and $\log_{10}[n + 1]$-transformed abundances at family level (stress 0.1539, Axis 1: 61.4%, Axis 2: 20.58%). *P*-values are Bonferroni corrected.

Sweep-net samples from 2005 revealed that family diversity of vegetation-living arthropods (Table 2) was highest in desert habitats, followed by xeric, mesic and remnant habitats. Pitfall samples for the same year found that mesic habitats were most diverse, and the xeric habitat had the lowest diversity. Desert and remnant habitats were intermediate.

3.4. Comparing spider and beetle communities at the family level

The spider (Araneae) communities consisted of 22 families and differed significantly among the habitats (NPMANOVA, $F = 10.41$, $P < 0.0001$, Morisita distance, $\log_{10}[n + 1]$-transformed), with mesic habitats significantly different from all the other habitats (Fig. 6). Analysis of covariance on the slopes of log-transformed ranks revealed significant differences in evenness (ANCOVA, $F_{1, 3} = 7.47$, $P = 0.0002$). The slopes were significantly different (desert $\beta_1 = -1.247$ vs. mesic $\beta_1 = -1.389$, $P < 0.0001$; mesic vs. remnant $\beta_1 = -1.062$, $P < 0.0001$; desert vs. xeric $\beta_1 = -1.473$, $P = 0.0015$; remnant vs. xeric $P < 0.0001$, Tukey–Kramer adjusted *P*-values) except for desert vs. remnant ($P = 0.1413$) and mesic vs. xeric habitats ($P = 0.7360$). Spider abundance was significantly correlated with precipitation in xeric habitats only (simple linear regression, $\log e$-transformed data, $F_{1, 5} = 6.752$, $R^2 = 0.575$, $P = 0.0483$). This relationship was not significant in the other habitats (desert: $F_{1, 5} = 1.019$, $R^2 = 0.169$, $P = 0.3592$; remnant: $F_{1, 5} = 1.328$, $R^2 = 0.210$, $P = 0.3013$; mesic: $F_{1, 5} = 0.0607$, $R^2 = 0.012$, $P = 0.8152$). Remnant habitats had on average higher spider diversity than desert followed by xeric habitats, and then mesic habitats had the lowest diversity overall (Table 3).
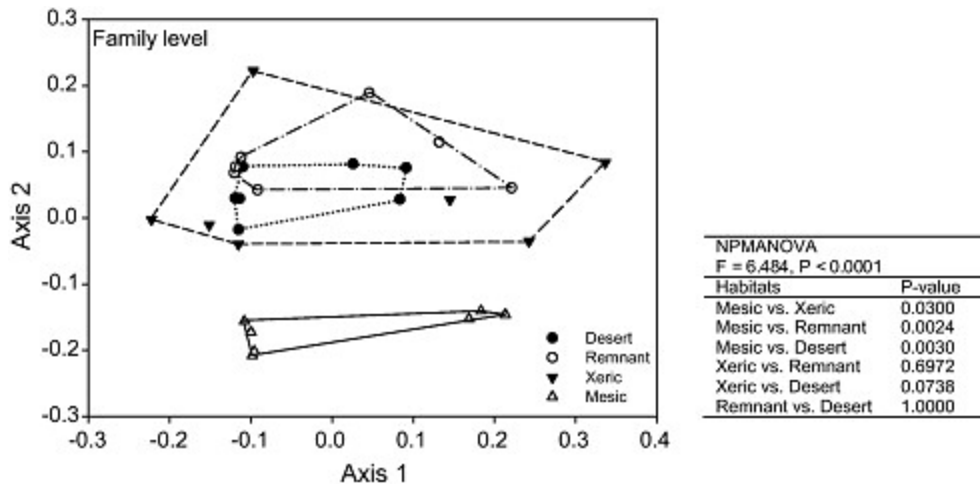
Fig. 6. Non-metric multidimensional scaling of annual pitfall samples, habitats and $\log_{10}[n + 1]$-transformed abundances of Araneae families (stress 0.1363, Axis 1: 51.4%, Axis 2: 34.74%). *P*-values are Bonferroni corrected.

Table 3. Diversity of arthropods within specific orders and families in four habitat categories from 2002 to 2008.

Year	Desert	Remnant	Xeric	Mesic
Taxonomic level: Araneae families[a]				
2002	3.63 ± 0.59	3.72 ± 0.75	9.28 ± 10.16	1.86 ± 0.26
2003	3.66 ± 0.46	5.32 ± 1.14	3.76 ± 0.86	2.24 ± 0.26
2004	2.88 ± 0.44	4.51 ± 0.72	2.33 ± 0.50	1.75 ± 0.23
2005	4.40 ± 0.69	5.86 ± 1.23	2.16 ± 0.51	2.43 ± 0.36
2006	2.77 ± 0.67		3.30 ± 1.28	2.15 ± 0.43
2007	4.21 ± 1.05	8.86 ± 4.58	0.80 ± 0.43	2.21 ± 0.46
2008	2.89 ± 0.63	2.39 ± 1.66	1.28 ± 0.59	1.64 ± 0.39
Taxonomic level: Coleoptera families				
2002	1.77 ± 0.31	1.16 ± 0.27	1.15 ± 0.34	3.03 ± 0.36
2003	1.87 ± 0.26	1.83 ± 0.33	3.14 ± 0.51	1.66 ± 0.21
2004	2.17 ± 0.30	1.44 ± 0.22	1.80 ± 0.38	2.19 ± 0.27

2005	1.92 ± 0.36	2.1 ± 0.36	2.56 ± 0.69	2.72 ± 0.33
2006	1.54 ± 0.29	0.6 ± 0.16	1.30 ± 0.42	2.57 ± 0.36
2007	1.83 ± 0.33	1.01 ± 0.21	1.34 ± 0.45	2.24 ± 0.35
2008	3.74 ± 0.76	1.6 ± 0.46	1.62 ± 0.47	2.44 ± 0.41
Taxonomic level: Formicidae genera				
2004	1.39 ± 0.16	1.11 ± 0.16	2.07 ± 0.31	1.81 ± 0.22
2005	1.56 ± 0.22	1.01 ± 0.17	1.25 ± 0.20	2.82 ± 0.38
2006	1.50 ± 0.16	1.71 ± 0.25	1.62 ± 0.27	1.93 ± 0.22
2007	2.02 ± 0.22	1.21 ± 0.16	2.28 ± 0.41	2.21 ± 0.25
2008	1.26 ± 0.15	1.88 ± 0.30	1.49 ± 0.27	1.49 ± 0.20
Taxonomic level: Tenebrionidae genera[b]				
2004	2.13 ± 0.50	1.48 ± 0.32	2.76 ± 1.51	0.80 ± 0.43
2005	3.02 ± 1.10	0.82 ± 0.27	0.38 ± 0.27	
2006	2.70 ± 0.49	1.24 ± 0.30	1.71 ± 0.68	0.46 ± 0.17
2007	2.01 ± 0.38	1.37 ± 0.28	0.94 ± 0.34	1.74 ± 0.99
2008	3.85 ± 1.02	2.22 ± 0.65	2.02 ± 0.87	

Notes: Fisher's α ± analytical standard deviation. These measures should be compared within year, not between years. [a]In 2006 remnant habitats had only three families with one individual in each. [b]In 2005 and 2008 mesic habitats contained only two and one individuals, respectively.

In beetle (Coleoptera) communities (24 families) mesic habitats were significantly different to all other habitats (Fig. 7; NPMANOVA, $F = 27.39$, $P < 0.0001$, Morisita distance, $\log_{10}[n + 1]$-transformed). Analysis of covariance on the slopes of log-transformed ranks revealed significant differences in evenness (ANCOVA, $F_{1, 3} = 3.22$, $P = 0.0291$). The slopes were significantly different (desert $\beta_1 = -0.975$ vs. remnant$\beta_1 = -1.463$, $P < 0.0001$; desert vs. xeric $\beta_1 = -1.401$, $P = 0.0001$; mesic $\beta_1 = -1.387$ vs. remnant$P < 0.0001$, Tukey–Kramer adjusted P-values). Desert and mesic habitats were not significantly different ($P = 0.0734$). Overall, mesic habitats had higher beetle diversity, followed by desert, xeric and then remnant habitats. Coleoptera abundance (including those identified to order only) was not significantly correlated with precipitation in any of the habitats (Table 3).
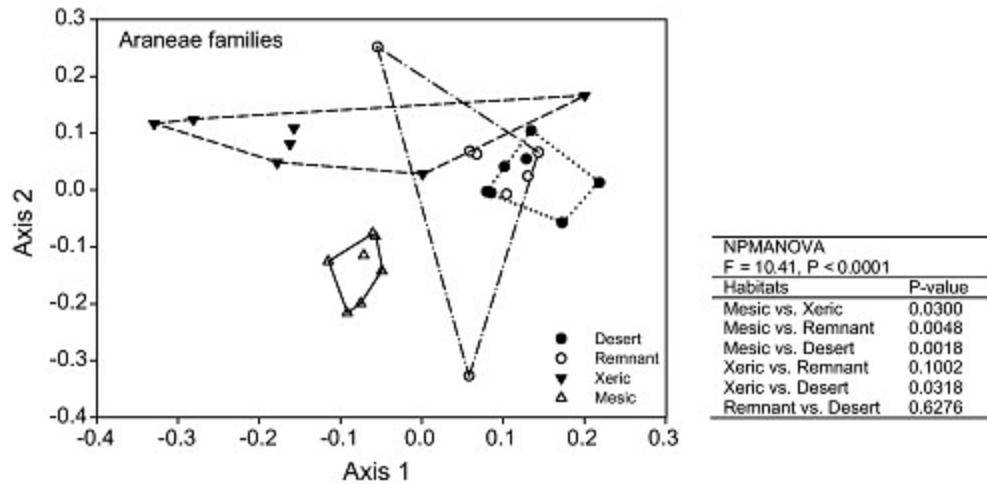
Fig. 7. Non-metric multidimensional scaling of annual pitfall samples, habitats and $\log_{10}[n + 1]$-transformed abundances, Coleoptera families (stress 0.1308, Axis 1: 88.46%, Axis 2: 0.02%). *P*-values are Bonferroni corrected.

3.5. Comparing communities at the genus level

Only the insect families Formicidae and Tenebrionidae had more than 30% of the specimens identified to genus. The adjusted abundance of the total families was tested against precipitation, but the relationship was not significant in any of the habitats. For the diversity measures, we excluded individuals identified to family or subfamily and focused on the ~30% identified to genus. There were no Formicidae identified to genus in desert 2002–2003, remnant in 2002, xeric in 2002–2003, or mesic in 2002–2003, and no Tenebrionidae identified to genus in 2002–2003. Because of the lack of identification at this level, we did not test for evenness.

Formicidae communities (21 genera) varied significantly by habitat (NPMANOVA, *F* = 14.53, *P* < 0.0001, Morisita distance, $\log_{10}[n + 1]$-transformed), with mesic habitats being significantly different from both desert and remnant habitats. NMS revealed a distinct pattern along the first axis (Fig. 8). The position of the communities in relation to each other was similar to previous patterns. The ant diversity in mesic habitats was on average higher than in all the other habitats (Table 3), and also in overall abundance (including those not identified to genus).

Fig. 8. Non-metric multidimensional scaling of annual pitfall samples, habitats and $\log_{10}[n + 1]$-transformed abundances, Formicidae genera (stress 0.116, Axis 1: 56.64%, Axis 2: 23.18%). *P*-values are Bonferroni corrected.

Although only 16 genera were identified in Tenebrionidae, the communities still differed among habitats (NPMANOVA, $F = 12.99$, $P < 0.0001$, Morisita distance, $\log_{10}[n + 1]$-transformed). The remnant habitat was significantly different from both types of urban residential yards, while desert was only different from xeric habitat. The NMS explains some of this pattern, since only xeric habitat with its valid outlier (only one genus in 2005) extends along the second axis (Fig. 9). Overall, the tenebrionid diversity is higher in the desert than the other habitats (Table 3), but since the data are incomplete for the mesic habitat (only one individual of the dominant species), no conclusions should be made based on this family. Remnant and desert habitats had the highest abundance overall, with mesic habitat having the lowest abundance (including those not identified to genus).

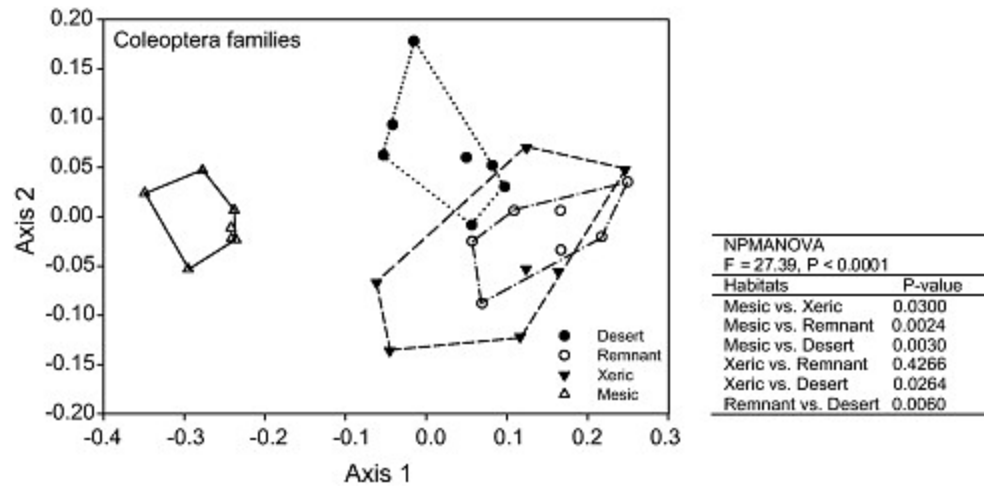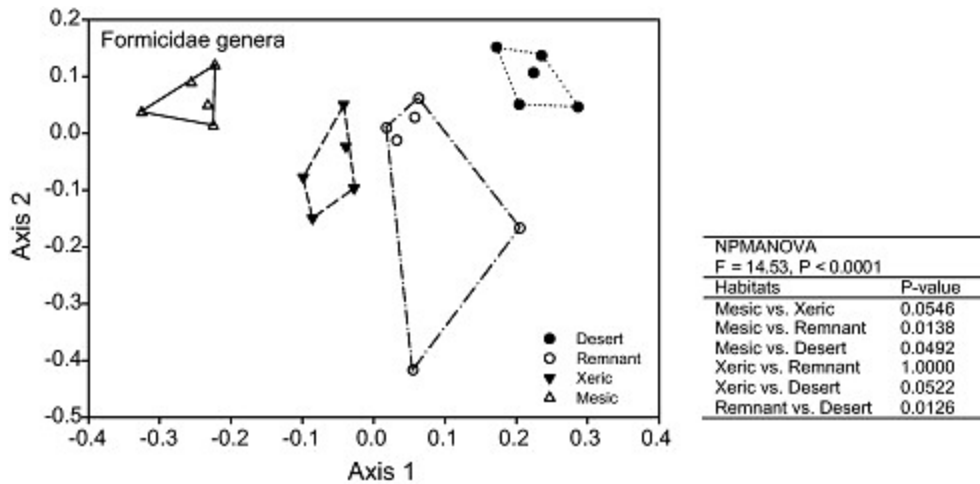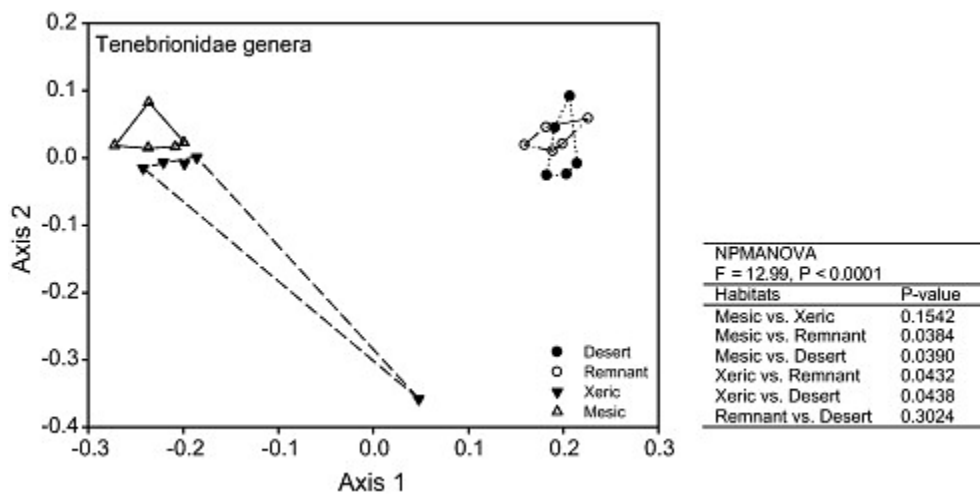**Fig. 9.** Non-metric multidimensional scaling of annual pitfall samples, habitats and $\log_{10}[n + 1]$-transformed abundances, Tenebrionidae genera (stress 0.1277, Axis 1: 70.31%, Axis 2: 12.26%). P-values are Bonferroni corrected.

3.6. Trophic levels and precipitation

Abundances of various trophic levels were tested against fluctuations in annual precipitation. Predator abundance in remnant habitats was significantly correlated with precipitation ($F_{1, 5} = 7.385$, $R^2 = 0.5963$, $P = 0.04189$), and for detritivores in remnant and xeric habitats ($F_{1, 5} = 10.17$, $R^2 = 0.6705$, $P = 0.02428$ (remnant) and $F_{1, 5} = 10.27$, $R^2 = 0.6726$, $P = 0.02387$ (xeric)).

3.7. Non-native ant taxa

Of the few taxa identified to genus or species, we were able to sort out 6 ant taxa not native to the state of Arizona (R. Johnson, personal communication): *Linepithema humile*, *Linepithema* sp., *Cardiocondyla* sp.,*Pyramica membranifera*, *Strumigenys lousianae* and *Strumigenys* sp. These were all found in mesic residential yards except one single individual of *Linepithema* sp. which was found in one of the remnant locations in 2008. These were normally not the dominant ant species, except for *L. humile*, which was the dominant ant species in one of the sites in 2006 and 2008. *L. humile* was the third most abundant ant taxa in mesic habitats after *Solenopsis* sp. (of which half were *S. xyloni*) and *Brachymyrmex* sp.

4. Discussion

Our goal with this paper was to identify differences in arthropod communities in response to urbanization, or more specifically, how different types of landscaping affect arthropod communities. The results suggest that the way land owners in urbanized areas manage their lawns and other landscape elements has a large influence on local arthropod communities. Our taxonomic shortcut – using order or family instead of finer taxonomic resolution – proved adequate to give a quick general impression of community structure in urban and rural habitats. These broader levels of identification, however, may mask important differences among taxonomically smaller, but nonetheless, important groups of arthropods. Here, we first discuss overall patterns in arthropod communities in this desert city, and then discuss major differences among specific groups.

4.1. Composition

Arthropod composition varies among land-use types, and the pattern is similar at all taxonomic levels examined. Mesic residential yards in this desert city have been converted from agricultural fields or former desert habitats and are characterized by year-round irrigation and maintenance of lawns and exotic plants. These habitats consequently contain a very different set of arthropods than arid desert habitats. Remnant habitats in Phoenix are visually comparable to the surrounding

desert with essentially similar plants and vegetation structure. This similarity was also reflected in arthropod composition, since arthropod communities in remnant habitats were generally more similar to desert arthropod communities than to those of other habitat types. Furthermore, arthropod communities in xeric residential yards were closer in composition to those of mesic yards than those of desert habitats, most likely due to supplemented irrigation and presence of non-native plants (Martin & Stabler, 2002). This relationship is not unique to this desert city, as components of vegetation have been found to be an important predictor of arthropod richness and abundance in urban domestic gardens (e.g., in Sheffield, UK (Smith, Warren, Thompson, & Gaston, 2006) and Toronto, Canada (Sperling & Lortie, 2010)). Land-use change was shown previously to be an important driver for arthropod communities in the Phoenix area (Cook and Faeth, 2006 and McIntyre et al., 2001), and it is therefore reasonable to assume that features of the habitat provide a 'template' on which arthropod composition is built (Faeth et al., 2011 and Grimm et al., 2008).

4.2. Abundance

The most striking abundance pattern in our study was that arthropod abundance in mesic residential yards was very high and fluctuations were completely decoupled from changes in precipitation (Fig. 3). Fluctuations in arthropod abundance in remnant and xeric habitats, on the other hand, were influenced by precipitation. Much of this seemed to be attributed to fluctuations in detritivore populations. Arthropods in arid areas respond to pulses in precipitation by increasing biomass and abundance, as deserts in general are bottom-up systems (Crawford, 1986). Our results suggest that arthropods living in these two urban habitats depend on ambient water, and that the supplementary irrigation in xeric yards is not sufficient to offset annual fluctuations. Mesic yards, on the other hand, with excessive irrigation and high productivity, alter abundance and richness patterns of arthropods. Due to year-round irrigation, plants remain productive and support higher abundances of arthropods at times when desert arthropods are dormant or absent due to lack of detritus and edible plant materials. This irrigation schedule is due to homeowners' attempts to maintain green lawns, trees and flowers (Martin & Stabler, 2002), leading to a buffering of seasonal changes (Faeth, Warren, Shochat, & Marussich, 2005).

The relationship between precipitation and arthropod abundance in desert habitats was weak and not significant. This may suggest that desert taxa are less sensitive to variations in precipitation, but may also be explained by local differences in precipitation patterns. When each desert location was tested against local precipitation measures (unpublished data), conflicting patterns were observed, suggesting different response mechanisms to precipitation. This should be further explored in more locations against different time lags.

4.3. Diversity

Despite the higher arthropod abundances in mesic habitats, arthropod diversity was generally lower than in desert habitats. Shochat et al. (2010) suggested that the decrease in evenness and

the dramatic change in community profile is a key to the complex process of diversity loss in urban areas. Our results indicate that the habitat features of mesic residential yards allow certain dominant taxa to increase in abundance more than other taxa, and thus lower the diversity. Productivity is also considered a driver for diversity, but often in a hump-shaped relationship (e.g., Mittelbach et al., 2001). Given that diversity seems to be lower than in low-productive desert habitats, the mesic habitats may be on the declining side of the hump. If that is the case, there should be other areas in this city with intermediate productivity and thus higher diversity, but this pattern was not apparent in any of our locations.

It is possible that this pattern is specific to the functional group studied. Common to many urban biodiversity studies, we focused on mobile, ground-dwelling arthropods, which consist of many detritivores, omnivores and predators (Appendix A and Appendix B). Our complementary sweep-net samples, however, reveal that arthropods associated with vegetation (largely herbivores and parasites) can be quite diverse in both mesic and desert habitats, suggesting a link between plant diversity (exotic or native) and plant-living arthropod diversity (e.g., Hunter & Price, 1992). For example, presence of native plants supported higher diversity of birds and butterflies in suburban landscapes of Pennsylvania (Burghardt, Tallamy, & Shriver, 2009). Remnant habitats, however, had lowest diversity from the sweep-net sampling in 2005, possibly reflecting the sparse vegetation in these areas. For future biodiversity-restoration projects, it is thus important to note that apparent visual improvements to biodiversity (i.e., plantings) do not necessarily improve diversity of higher trophic levels.

4.4. Predators and specialists

Underlying patterns for the differences in arthropod composition are evident at finer taxonomic scales, where differences within orders and families were observed. For example, spiders were more diverse in the desert, while beetles were more diverse in mesic yards. Remnant habitats had the highest spider family diversity overall, but the lowest beetle family diversity and ant diversity. Together with scorpions, spiders may be the most important predatory arthropods in the desert, where abundance and diversity are controlled by the limited water supply and low productivity (Polis & Yamashita, 1991). Predators play an important role in structuring desert food webs, and in more productive habitats, plants provide refuge for smaller ectothermic predators (Ayal, 2007). An earlier study also showed that productive habitats such as the mesic yards had higher spider abundance, but lower diversity than less-productive habitats (Shochat et al., 2004). Of note, predator taxa such as scorpions and solifugids were completely absent from mesic habitats. This could reflect that the humid habitat is less preferable for some desert organisms. Spider abundance was correlated with precipitation in xeric habitats, suggesting a bottom-up pattern mimicking desert trophic dynamics. Similarly, predators and detritivores also increased in wet years in remnant areas, suggesting a similar bottom-up dynamic. Further studies of differences in predator diversity and abundance may clarify the structuring mechanisms associated with urbanization.

The beetle family Tenebrionidae was nearly absent from the mesic habitat, but was diverse in the desert. Tenebrionids are usually detritivores strongly adapted to the environment in which they live, and many species are specifically associated with desert communities (Crawford, 1991). This suggests that we lose specialist species or specialist groups in heavily urbanized areas. Ant diversity was highest in mesic habitats, and this is also where we found non-native ant taxa. Some of the species that we found, in particular the Argentine ant, *L. humile*, are known to replace native species and change native arthropod communities (Holway, 1999). Some native ant taxa were never found in the mesic habitats.

4.5. Taxonomic resolution

We have presented arthropod data at different taxonomic resolutions. While the ideal for all monitoring situations would be identification to species, this is rarely feasible in practice. Using non-parametric tools coupled with some caution in interpretation, however, the LPT and family levels both give good overall pictures of how arthropod communities respond to urbanization. Although there are many uncertainties within some families, these resolutions give us the opportunity to assess general feeding preferences and thus trophic relationships. This advantage is lost if diversity assessments rely only on morphospecies (e.g.,Oliver & Beattie, 1996). Therefore, we instead recommend LPT- or family-level resolutions for long-term monitoring.

As we have also demonstrated, much information is lost if the analyses are limited to these two levels. The order level revealed similar general trends as the family and LPT levels, but the resolution was poor. Breaking the taxa into groups or specific families and orders revealed that some groups responded positively to urbanization, while others responded negatively. Moreover, without species-specific knowledge, it is difficult to distinguish between invasive and native species. Furthermore, because conclusions about urbanization effects on diversity depend on functional group (ground-dwelling arthropods vs. vegetation-living arthropods), we recommend that diversity assessments always measure different functional groups. Analyses at the family or LPT level should be reported, and supplemented with analyses of specific groups for which there is available taxonomic expertise.

4.6. Conclusion

Urban habitats can be repositories for biodiversity (Bradshaw, 2002 and Rosenzweig, 2003), but our results suggest that both arthropod composition and interactions are drastically altered in cities. Faeth et al. (2005) suggested that remnant areas acquire generalist species from surrounding neighborhoods, replacing some native species. Remnants are the habitats that are often the focus of attempts to conserve or enhance native species diversity in cities (e.g., Rosenzweig, 2003). However, remnant areas are often subject to profound environmental stresses and invasions (Miller & Hobbs, 2002), although they may still ostensibly resemble wild habitats in vegetation structure. Although our analysis spans seven years, we did not observe such a synanthropization (increase of species ecologically associated with humans) of arthropods

in remnant habitats in the CAP LTER urban area. A more detailed identification of the specimens, however, may reveal such changes.

In terms of landscaping methods in residential yards, our study suggests that a homeowner's choice can greatly affect arthropod communities. A landscape that resembles the local surrounding environment is usually advocated for native arthropods to thrive. However, our results indicate that human-made environments are unlikely to harbor the same arthropod associations as natural environments. A focus on mechanisms behind landscaping methods and arthropod communities will make us better understand how to sustain native arthropod communities in urban environments.

Acknowledgements

Appendix A.

Arthropod taxa from pitfall samples, Central-Arizona Phoenix metropolitan area, 2002–2008.

Class	Order	Family		Genus	Species	Guild	Habitat
		Superfamily	Subfamily				
Arachnida							
1 Acari (subclass)						n/a	D/R/X/M
2	Amblypygi					C	D
3			Araneae			C	D/R/X/M
4		Araneidae				C	D/R/M
5		Linyphiidae				C	D/R/X/M
6		Nesticidae				C	D/R/X/M
7		Tetragnathidae				C	D/M
8			Tetragnathinae	*Glenognatha*		C	M
9		Theridiidae				C	D/R/X/M
10			Latrodectinae	*Latrodectus*		C	D
11			Theridiinae	*Tidarren*		C	M
12			Hadrotarsinae	*Dipoena*		C	R
13				*Euryopis*		C	D/R/X
14			Pholcommatinae	*Pholcomma*		C	D/X/M
15			Latrodectinae	*Steatoda*		C	D/M
16		Caponiidae				C	D/R/X/M
17		Liocranidae				C	D

#							
18				*Agroeca*		C	D
19		Dictynidae				C	R/X/M
20		Oonopidae				C	D/R/M
21				*Scaphiella*		C	D/X
22		Oecobiidae				C	R/X/M
23				*Oecobius*		C	X/M
24		Gnaphosidae				C	D/R/X/M
25			Drassodinae	*Drassodes*		C	R
26			Zelotinae	*Drassyllus*			C
27			Gnaphosinae	*Gnaphosa*		C	D
28			Micariinae	*Micaria*			C
29			Echeminae	*Scopoides*		C	D
30			Zelotinae	*Zelotes*		C	D/R/X/M
31		Lycosidae				C	D/M
32			Allocosinae	*Allocosa*		C	M
33			Lycosinae	*Hogna*		C	M
34				*Alopecosa*		C	D/M
35				*Arctosa*		C	R/M
36				*Lycosa*		C	D/R/X/M
37			Pardosinae	*Pardosa*		C	M
38		Oxyopidae				C	D/R/M
39				*Oxyopes*			C
40		Mimetidae				C	D
41			Mimetinae	*Mimetus*		C	D/R
42		Clubionidae				C	D/R/X/M
43		Pholcidae				C	D/R/X/M
44				*Psilochorus*		C	D/R/X
45		Plectreuridae				C	D/R/X/M
46				*Plectreurys*		C	M
47		Salticidae				C	D/R/X/M
48				*Peckhamia*		C	X
49			Dendryphantinae	*Metaphidippus*		C	D
50			Pelleninae	*Habronattus*		C	D/R/M
51		Scytodidae				C	D/R
52				*Scytodes*		C	X
53		Sicariidae		*Loxosceles*		C	D/R/M
54		Philodromidae				C	D/R/M
55		Thomisidae				C	D/R/M
56			Thomisinae	*Coriarachne*		C	D/M
57				*Xysticus*		C	D/R
58	Opiliones					C	D/R/X/M
59	Pseudoscorpiones					C	D/R/X
60	Scorpiones					C	D/R/X
61		Iuridae				C	D/R
62		Vaejovidae				C	D/R
63	Solifugae					C	D/R/X
64		Eremobatidae				C	D
65 **Chilopoda**						C	D/R/X/M
66	Scutigeromorpha					C	D
67	Lithobiomorpha					C	M

No.	Order	Family	Subfamily	Genus	Species		
68	Scolopendromorpha	Scolopendridae				C	R
69**Collembola**							
70	Entomobryomorphae	Entomobryidae				D	D/R/X/M
71		Isotomidae				D	D/R/X/M
72	Poduromorpha	Hypogastruridae				D	D/R/X/M
73	Symphypleona	Sminthuridae				D	D/R/X/M
74**Diplopoda**						D	D/R/X/M
Insecta							
75	Archaeognatha	Meinertellidae				D	D/R
76	Blattaria					O	D
77		Blattidae				O	R/X/M
78		Polyphagidae				O	D/R/X
79				*Arenivaga*		O	D/R
80	Coleoptera					n/a	D/R/X/M
81		Dermestidae				D	M
82		Heteroceridae				D	M
83		Carabidae				C	D/R/X/M
84			Harpalinae	*Agonum*		C	M
85				*Amara*		H	D
86				*Pterostichus*(Argutor)		C	M
87				*Selenophorus*		C	D/R/X/M
88				*Syntomus*		C	D/R/X/M
89					*americanus*	C	D/R/X/M
90				*Tetragonoderus*		C	D/R/X
91			Scaritinae	*Scarites*		C	M
92			Trechinae	*Bembidion*		C	D
		Cicindelidae					
93			Cicindelinae	*Cicindela*(Cicindelidia)		C	R/X/M
94		Chrysomelidae				H	D/R/X/M
95			Bruchinae			H	X
96				*Gibbobruchus*		H	X
97				*Zabrotes*		H	X
98			Cryptocephalinae	*Pachybrachis*		H	M
99			Galerucinae	*Chaetocnema*		H	D/X/M
100				*Syphrea*		H	D
101		Melyridae				n/a	D/R/X
102				*Collops*		C	D
103		Coccinellidae				C	D/R/X/M
104		Corylophidae				F	D/R/X/M
105		Cryptophagidae				F	X
106				*Cryptophagus*		F	M
107		Cucujidae				C	M

108		Lathridiidae				F	R/X/M
109			Corticariinae	*Melanophthalma*		F	D
110				*Migneauxia*		D	X
111		Nitidulidae				D	M
112			Carpophilinae	*Carpophilus*		F	M
113		Curculionidae				H	D/R/X/M
114			Dryophthorinae	*Sphenophorus*		H	M
115			Scolytinae			H	M
116		Elateridae				H	D/X/M
117			Agrypninae	*Agrypnus*		H	M
118				*Aeolus*		H	M
119				*Conoderus*		H	M
120		Histeridae				C	D/R
121			Saprininae	*Eremosaprinus*		C	D
122				*Geomysaprinus*		C	D/R/M
123		Scarabaeidae				D	D/R/X/M
124			Aphodiinae	*Ataenius*		D	R/M
125				*Tesarius*		D	M
126		Leiodidae				F	D/R/X/M
127			Cholevinae	*Ptomaphagus*		F	D/R/X/M
128				*Ptomaphagus*(Adelops)		F	D
129		Ptiliidae				F	M
130		Staphylinidae				C	D/R/X/M
131			Aleocharinae	*Melanalia*		C	M
132			Osoriinae	*Osorius*		C	M
133			Oxytellinae	*Apocellus*		C	M
134			Phloeocharinae	*Charhyphus*		C	D/X/M
135			Pselaphinae			C	D
136				*Ctenisis*		C	D
137			Scydmaeninae			C	D
138				*Papusus*		C	D
139			Staphylinae	*Platydracus*		C	M
140		Anthicidae				O	D/R/X/M
141			Anthicinae	*Formicilla*		O	D/M
142				*Vacusus*		O	M
143		Meloidae				n/a	D
144				*Eupompha*		H	D
145				*Lytta*		H	D
146			Meloinae	*Epicauta*		H	D
147		Mycetophagidae				D	D/M
148		Tenebrionidae				D	D/R/X/M
149			Opatrinae	*Blapstinus*		O	D/X/M
150				*Cheirodes*		U	D/X
151				*Conibius*		U	D
152				*Eleodes*		D	D/R
153					*armatus*	D	D/R/X
154				*Nocibiotes*		D	D/R/X/M
155					*granulatus*	D	D/R/X/M
156				*Trichoton*		D	X

#	Order	Family	Subfamily	Genus	Species		
157			Pimeliinae	*Alaudes*		U	D
158				*Asidina*		D	D/R
159					*parallela*	D	D/R
160					*wickhami*	D	X
161				*Anepsius*		D	D/R
162				*Araeoschizus*		D	D/R
163					*sulcicollis*	D	R
164				*Centrioptera*		D	D/R
165					*muricata*	D	D/R
166				*Steriphanus*		D	D/X
167				*Trichiasida*		D	D
168					*hirsuta*	D	D
169					*hispidula*	D	D
170				*Triorophus*		D	D/R
171			Tenebrioninae	*Argoporis*		D	D/R
172					*bicolor*	D	D
173				*Zophobas*		D	M
174		Zopheridae				D	X
175			Monommatinae	*Hyporhagus*		D	X
176	Dermaptera					O	M
177		Labiduridae				O	M
178		Labiidae				O	X/M
179			Embiidina			H	D/R/X/M
180		Oligotomidae				H	D/X
181	Hemiptera					n/a	D/R/X/M
182			Anthocoridae			C	D/R/X/M
183			Anthocorinae	*Orius*		C	R
184		Cydnidae				H	D/R/X/M
185				*Melanaethus*		H	D/R/M
186		Enicocephalidae				C	D/M
187		Geocoridae		*Geocoris*		C	D/M
188					*pallens*	C	R
189					*punctipes*	C	M
190		Lygaeidae				H	D/R/X/M
191			Lygaeinae	*Lygaeus*		H	M
192				*Neacoryphus*		H	D
193			Orsillinae	*Nysius*		H	D/R
194		Miridae				n/a	D/R/X/M
195			Mirinae	*Phytocoris*		C	D
196			Phylinae	*Rhinacloa*		O	M
197		Nabidae				C	D
198				*Pagasa*		C	R
199		Pentatomidae				n/a	X/M
200		Reduviidae				C	D/R/X
201		Rhopalidae				H	D
202				*Aufeius*		H	D
203				*Harmostes*		H	D
204				*Niesthrea*		H	X
		Rhyparochromidae					
205			Rhyparochrominae	*Cnemodus*		H	X
206				*Prytanes*		H	M

207		Saldidae				C	M
208		Tingidae				H	D/R/X/M
209			Tinginae	Corythucha		H	D
210		Coccoidea				H	D/R/X/M
211	Homoptera					n/a	D/M
212		Aleyrodidae				H	D/R/X/M
213		Aphididae				H	D/R/X/M
214		Cercopidae				H	R/M
215		Cicadellidae				H	D/R/X/M
216				Hebecephalus		H	M
217			Agalliinae	Aceratagallia		H	D/X/M
218			Cicadellinae	Carneocephala		H	M
219			Deltocephalinae	Athysanella		H	R/M
220				Exitianus		H	D
221		Delphacidae				H	X/M
222		Membracidae				H	D/R
223		Psyllidae				H	D/R/X
224	Hymenoptera	Mutillidae				P	D/R/X/M
225			Myrmosinae			P	D
226		Formicidae				n/a	D/R/X/M
227			Dolichoderinae	Dorymyrmex		O	D/X/M
228					insanus	O	D/R/X/M
229				Forelius		O	D/R/X/M
230					mccooki	O	D/R/X/M
231					pruinosus	O	D/R/X/M
232				Linepithema		O	R/M
233					humile	O	M
234			Ecitoninae	Neivamyrmex		C	D/R/M
235			Formicinae	Myrmecocystus		O	D/R/X
236				Paratrechina		O	R/X/M
			Myrmicinae	Aphaenogaster			
237					cockerelli	O	D
238				Brachymyrmex		O	D/X/M
239				Cardiocondyla		O	M
240				Crematogaster		O	D/R/X
241				Leptothorax		O	D
242				Messor		H	D
243					pergandei	H	D
244				Monomorium		H	R/X/M
245				Pheidole		n/a	D/R/X/M
246					californica	H	D
247					desertorum	O	D/R/X
248					micula	O	D
249					tetra	O	D/M
250					tucsonica	H	D
251				Pogonomyrmex		O	D/R
252					californicus	H	D/R
253					rugosus	O	D/R/M

#	Order	Family / Superfamily	Subfamily	Genus	Species	Guild	Habitat
254				(Ephebomyrmex)		H	D/R/X
255				*Pyramica*		C	M
256					*membranifera*	C	M
257				*Solenopsis*		O	D/R/X/M
258					*amblychila*	O	D/R/X/M
259					*aurea*	O	D
260					*xyloni*	O	D/R/X/M
261				(Diplorhoptrum)		O	D/R/X/M
262				*Strumigenys*		C	M
263					*louisianae*	C	M
264				*Tetramorium*		O	D/R/X
265			Ponerinae	*Hypoponera*		C	X/M
266				*Odontomachus*		C	M
267	Isoptera					H	M
268		Kalotermitidae				H	M
269		Termitidae				H	D/R/X/M
270	Mantodea					C	D/R/X
271		Mantidae				C	D
		Mantinae	*Iris*				
272					*oratoria*	C	D
273	Orthoptera	Acrididae				H	D/R/X
274		Gryllidae				O	D/R/X/M
		Rhaphidophoridae					
275			Rhaphidophorinae			D	R
276		Gryllacrididae				C	D/R
277	Phasmatodea	Heteronemiidae				H	D
278	Psocoptera					D	D/R/X/M
279	Siphonaptera					P	R
280	Thysanoptera					H	D/R/X/M
281		Phlaeothripidae				H	X/M
282		Thripidae				H	D/R/X/M
283	Zygentoma	Lepismatidae				D	D/R/X/M
Malacostraca							
284	Isopoda					D	D/R/X/M

Guilds: C, carnivore; D, detritivore; F, fungivore; H, herbivore; O, omnivore; P, parasite; U, unknown. *Habitats*: D, desert; R, remnant; X, xeric; M, mesic.

Appendix B.

Arthropod taxa from sweep-net samples, Central-Arizona Phoenix metropolitan area, 2005.

Class	Order	Family		Genus	Species	Guild	Habitat
		Superfamily	Subfamily				

Arachnida							
1	Araneae	Anyphaenidae				C	X
2				*Aysha*		C	M
3		Araneidae				C	D/M
4		Dictynidae				C	D/R/X/M
5		Lycosidae		*Pardosa*		C	D
6		Mimetidae				C	D/X
7		Oxyopidae				C	R
8		Philodromidae				C	X
9		Salticidae				C	D/R/X/M
10		Theridiidae				C	D/R/X/M
11				*Tidarren*		C	X
12		Thomisidae				C	D/R/X
Collembola							
13	Entomobryomorpha	Entomobryidae				D	M
14	Symphypleona	Sminthuridae				D	D
Insecta							
15	Coleoptera	Bruchidae		*Callosobruchus*		H	D
16		Buprestidae				H	D
17		Chrysomelidae				H	X/M
18		Cleridae					C
19		Coccinellidae				C	D/X/M
20				*Hippodamia*		C	M
21		Corylophidae				F	X
22		Curculionidae				H	D/R
23		Melyridae				n/a	D/R
24		Nitidulidae				D	M
25		Staphylinidae				C	D/M
26	Diptera	Agromyzidae				H	D/R/M
27		Anthomyiidae				H	D/R/M
28		Cecidomyiidae				H	D/X/M
29		Chironomidae				D	D/R/X/M
30		Chloropidae				O	D/X/M
31		Empididae				C	R/X
32		Heleomyzidae				D	M
33			Trixoscelidinae			D	D/X
34		Muscidae				D	X
35		Scatopsidae		*Psectrosciara*		D	X
36		Sciaridae				F	D/X/M
37		Syrphidae				H	X
38		Tachinidae				P	M
39		Tephritidae				H	D/R/X/M
40		Tipulidae				H	X
41	Hemiptera	Anthocoridae				C	D/R/X/M
42		Geocoridae		*Geocoris*		C	M
43		Lygaeidae				H	D/X/M
44				*Nysius*		H	D/X/M
45		Miridae				n/a	D/R/X/M
46				*Calocoris*		H	D/R
47				*Rhinacloa*		O	R
48		Nabidae				C	D/R
49		Pentatomidae				n/a	D/R/X
50		Reduviidae				C	D/X/M
51		Rhopalidae				H	D/R
52		Tingidae				H	D/R
53				*Corythucha*		H	R
54	Homoptera	Aleyrodidae				H	D/X/M
55		Aphididae				H	D/R/X/M
56		Cicadellidae				H	D/R/X/M

#	Order	Family	Subfamily	Genus		Guild	Habitat
57				*Aceratagallia*		H	X
58				*Carneocephala*		H	M
59				*Cloanthanus*		H	D
60				*Empoasca*		H	D/R/M
61		Cixiidae				H	M
62		Membracidae				H	D/R/X/M
63		Psyllidae				H	R/X
64	Hymenoptera	Agaonidae				H	X
65		Braconidae				P	D/X/M
66		Chalcidoidea				P	D/R/M
67		Chrysididae				P	D
68		Encyrtidae				P	M
69		Eulophidae				P	D/R/M
70		Eurytomidae				P	M
71		Figitidae				P	D
72			Eucoilinae			P	M
73		Formicidae				n/a	D
74			Dolichoderinae	*Linepithema*		O	M
75			Myrmicinae	*Brachymyrmex*		O	X/M
76				*Myrmecocystus*		O	M
77				*Paratrechina*		O	M
78		Ichneumonidae				P	D/X
79		Megaspillidae				P	D/X
80		Mymaridae				P	D
		Platygastridae					
81			Scelioninae			P	D/R/M
82		Pteromalidae				P	D/R/M
83		Sphecidae				P	D/X
84		Tanaostigmatidae				P	R
85		Torymidae				P	D/M
86		Trichogrammatidae				P	D/M
87	Lepidoptera	Blastobasidae				D	D
88		Geometridae				H	D/R/X/M
89		Pyralidae				H	D
90	Neuroptera	Chrysopidae				C	D/R/X/M
91		Hemerobiidae				C	D/M
92	Thysanoptera	Aeolothripidae				H	R/M
93		Thripidae				H	R

Guilds: C, carnivore; D, detritivore; F, fungivore; H, herbivore; O, omnivore; P, parasite; U, unknown.

Habitats: D, desert; R, remnant; X, xeric; M, mesic.

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