ARBUSCULAR MYCORRHIZAL AND DARK SEPTATE ENDOPHYTIC FUNGI IN URBAN PRESERVES AND SURROUNDING SONORAN DESERT

by

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ACCEPTED BY THE GRADUATE COLLEGE

ABSTRACT

The creation of urban preserves has been proposed as a method of reducing the impact of urbanization on biodiversity of native ecosystems. This research compared root colonization by two important fungal root symbionts, arbuscular mycorrhizal (AM) fungi and dark septate endophytes (DSE), at two urban desert preserves located in Phoenix, Arizona and at two adjacent Sonoran desert sites. Diversity of AM fungi was compared between sites. AM root colonization was greater in surrounding deserts in comparison to urban preserves, but root colonization by DSE was not significantly different. A greater number of AM fungal species was detected in surrounding deserts in comparison to urban preserves, although the number of species/samples was not significantly different. There was also an absence of species from the *Acaulosporaceae* family at urban preserves. Decreases in AM root colonization and diversity observed at urban preserves may reduce the ability of preserves to sustain biodiversity.

To my family

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Introduction

Increasing attention has been given to the impact of urbanization on biodiversity because of the expansion of cities worldwide (McDonnell and Hahs 2008). Disruption of habitats, the introduction of exotic species, increase of pollutants, impervious surfaces and average ambient temperature ("urban heat island" effect), and alteration in biogeochemical cycling are among the anthropogenic perturbations (Lohse et al. 2008; McKinney 2002) associated with considerable shifts in community structure (McDonnell and Hahs 2008). As reviewed by McDonnell and Hahs (2008), the response of native species to urbanization is not uniform. Some studies have found that biodiversity and species richness are negatively impacted in urban ecosystems in comparison to preserved peripheral communities (Czech et al. 2000; McKinney 2002; McKinney 2006). In contrast, findings from the Baltimore Ecosystem Study (Pickett et al. 2008) have reported that biodiversity can be high in cities and include both native and exotic species.

Birds are the most common organismal group studied with regard to response to urbanization (49% of the 201 papers reviewed by McDonell and Hahs 2008). Studies of changes to bird community structure due to urbanization have reported some general trends in urban ecosystems including an increase of avian density especially by urban specialists and reduction of species diversity in the urban core (Blair 1996; Degraaf and Wentworth 1981; Marzluff 2001; Shochat et al. 2004). Other biotic community components including plants, mammals, butterflies and lizards might also be negatively impacted by urbanization (McKinney 2002). Some studies have demonstrated increases in species richness in urban areas including that of plants (Hope et al. 2003) and populations of arthropods (herbivorous, predatory and detritivores) (Cook and Faeth 2006).

Even though there are many studies that compare the diversity of plants and animals in urban areas with the surrounding natural ecosystem, similar studies of fungi are rare (less than 1% of studies as reviewed by McDonnell and Hahs 2008). Plant roots can be colonized by several

types of fungi, including saprophytic, pathogenic and mycorrhizal species. Mycorrhizal fungi are important microbiota that form an often mutualistic symbiosis (Brundett 2004) with the roots of terrestrial plants; in which fungi receive carbon compounds from the host plant and assist in mineral uptake (Allen 1991). In this association, photosynthetically derived carbon compounds (carbohydrates) travel from plant to fungus, and the inorganic compounds (water and nutrients) move from the fungus to the plant (Brundett 2004). Mycorrhizae confer many benefits to hosts plants such as improved absorption of soil nutrients and water, resistance to pathogens, better establishment and survival in stressful environments, and tolerance to drought (Brundett 2008). Mycorrhizae are widespread in almost all plants and in a wide range of ecosystems (Allen 1991). Arbuscular mycorrhizal (AM) fungi are the most common and oldest type of mycorrhiza (Redecker et al. 2000), which typically form arbuscules, hyphae and vesicles within roots (Brundett 2008).

Another group of fungi that colonize plant roots are the dark septate endophytes (DSE). These fungi are mainly classified in the phylum Ascomycota and have been found in over 600 plant species, especially plants growing in extreme environments (Jumpponen and Trappe 1998; Jumpponen 2001). DSE are often found between the root epidermis, cortex and in some cases in vascular tissue as thin-walled fungal cells with septa (Jumpponen 2001; Barrow 2003; Barrow and Aaltonen 2001). DSE also form microsclerotia (inflated cells) that grow inter and intra-cellularly within the cortex. Their characteristic dark color is due to the incorporation of melanin, a natural dark pigment that is also a fungal wall component (Barrow and Aaltonen 2001). Their ecological role requires further research to be clarified, but some studies suggested that DSE could function in root protection and growth stimulation (Barrow and Aaltonen 2001; Barrow and Osuna 2002; Jumpponen 2001). Barrow and Aaltonen (2001) postulate that the abundant and widespread occurrence of DSE in roots of desert plants suggests that these fungi have a

significant ecological function in arid ecosystems and may aid plants under the severe nutrient and water stress conditions found in these areas.

There are a limited number of studies that examine the impact of urbanization on root colonizing fungi primarily conducted in and around the Phoenix metropolitan area in the arid southwestern of USA. Stabler et al. (2001) found that AM fungal colonization was greater in roots of native trees growing in a desert remnant adjoining a residential area than in native trees growing in a residential area. They also reported more diverse types of AM fungal species associated with native trees at the remnant urban site than those at nearby residential landscapes. Cousins et al. (2003) suggested that AM species composition in urban areas was associated with plant communities and was the highest when samples came from native vegetation. They also found that AM species richness and mean spore density were greater at desert sites than at agricultural and urban-residential sites. According to Bills and Stutz (2009), the mean number of AM fungal species observed per plant and per site and the total number of AM fungal species from desert sites were greater than from the urban sites. Bills and Stutz (2009) also concluded that there were noticeable differences between AM fungal species found in their study of the deserts surrounding Phoenix and AM fungal species found by Stabler et al. (2001) and by Cousins et al. (2003) in urban desert sites in the Phoenix metropolitan area.

Because of the impact of urbanization on biodiversity, McKinney (2002) suggested two possible strategies to encourage the conservation of native species in urban ecosystems; the preservation of natural urban remnants and the restoration of habitats. Nevertheless, these strategies could fail in the attempt to preserve the biodiversity of native species. For example, non-native invasive plants and animals can colonize urban preserves and reduce the ability of urban remnants to support native species (McKinney 2002). There are other several factors that have been shown to affect the success of natural urban remnants to support native species. For

instance, in a survey of 29 reserves that differed in size and surrounding landscape (which was divided in urban, suburban, and exurban), Donelly and Marzluff (2004) found that bird species richness was greater and less even in larger reserves for all landscapes than in smaller reserves due to the presence of greater habitat diversity in larger reserves that can support a larger number of bird species. However, large reserves surrounded by more urbanized landscapes had greater bird species richness than large reserves surrounded by exurban landscapes because of the increase of synanthropic species (associated with humans). They also suggested that exotic ground and shrub vegetation reduced the presence of native species and increased the presence of synanthropic species. Knapp et al. (2008) determined that the size of the protected area influences diversity in the studied taxa (carabids, butterflies, snails, birds, lichens, mosses and vascular plants). A recent study of arthropod communities in the Phoenix metropolitan area reported differences in species composition between peripheral deserts and urban desert remnants (Cook and Faeth 2006). Although previous studies have assessed differences in AM fungal root colonization and diversity in urban sites in the Phoenix metropolitan area and in the outlying Sonoran Desert; a comparison between the AM fungal root colonization and diversity in urban desert remnants with the peripheral Sonoran Desert has not been conducted.

The purpose of this study was to analyze AM and DSE colonization of plant roots and AM fungal diversity at two urban desert preserves and two Sonoran desert sites surrounding the Phoenix metropolitan area. Based on previous research with arthropods, bird community and AM fungi in urban desert ecosystem, we hypothesize that AM fungal colonization and diversity associated with plants growing in urban desert preserve sites will be lower than AM fungal colonization and diversity associated with plants growing in the desert sites surrounding the Phoenix metropolitan area. Negative factors known to occur in urban ecosystems such as soil disturbance and compaction (Entry et al. 2002) and high levels of nitrogen (Siguenza et al. 2006)

have been demonstrated to decrease AM root colonization and diversity (Johnson 1993; Egerton-Warburton and Allen 2000; Egerton-Warburton et al. 2001). We also expect that DSE colonization will differ among the urban desert preserves and surrounding deserts from disturbance in urban ecosystems. This current study provides new information about differences between these areas and attempts to analyze the utility of urban remnants in preserving AM and DSE root colonization and AM fungal diversity in urban desert ecosystems.

Materials and methods

Site description and sampling methods

Arizona is the second-fastest growing state in the United States with a total population of 6,629,455 in 2008 (Arizona Department of Commerce 2009). Phoenix is the capitol and largest city of Arizona with a total population of 4,179,427 (Arizona Indicators 2009). Temperatures in Phoenix are 38°C or above an average of 90 days of the year, mostly between June and September. The mean annual precipitation is 180 mm with rainfall occurring in a bimodal pattern consisting of thunderstorms between July and September and frontal storms in December and January. Winters bring mild, sunny days, with occasional fog. Snow is rare, but frost is common in winter months. The minimum mean monthly temperature occurs in January (5 °C) and the maximum mean monthly temperature occurs in July (41° C) (Arizona State Climate Office 2009).

Four study sites were selected from existing study sites that are part of the Central Arizona-Phoenix Long-Term Ecological Research (CAP LTER) Survey 200 project. Two sites were selected in urban desert preserves and two in the Sonoran desert surrounding Phoenix. The study zone of the CAP LTER (Fig. 1), an area of ~6400 km2, involves a mosaic of urban residential, industrial and commercial sites, farms, deserts parks and surrounding deserts (Cook and Faeth 2006). Survey 200 was developed as an extensive field project to conduct long-term monitoring at 204 sites in the Phoenix metropolitan area and surrounding Sonoran Desert. In 2000 and 2005, several variables were measured at each site including land use, soil properties, plant, bird, and insect diversity (Grimm 2005).

For purposes of this study, an urban desert preserve was considered an area of importance to desert wildlife and flora that is protected from development and is within or mostly surrounded by the city. A surrounding desert was understood as a site primarily outside of the city where

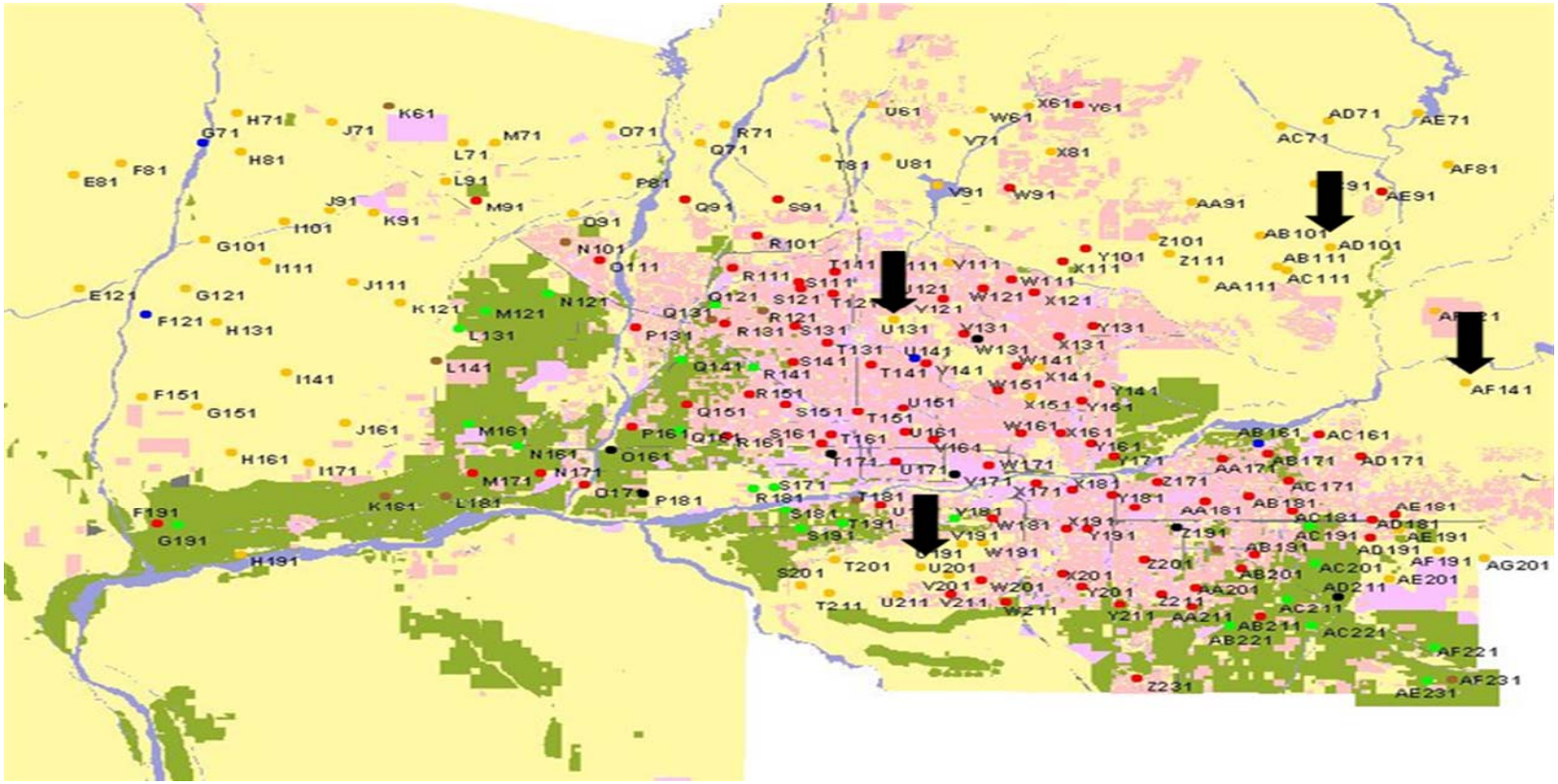

Fig. 1 Map of Central Arizona-Phoenix Long-Term Ecological Research (CAP LTER) Survey 200 sites. The colors in the map indicate different land use. Pink: urban and suburban sites, green: agriculture sites, and yellow: desert sites. The four arrows point to the study sites U131, U201, AD101 and AF141.

urban development is scarce. The study sites (Fig. 2) were selected based on location, accessibility and similar plant communities and included two study sites located in two different urban desert preserves, North Mountain Preserve (hereafter referred to as U131) and South Mountain Park (hereafter referred to as U201), and two study sites located in the Sonoran desert surrounding Phoenix metropolitan area, one located in McDowell Mountain Regional Park (hereafter referred to as AD101) and a second located in the Goldfield Mountain section of Tonto National Forest (hereafter referred to as AF141). The four study sites differed in their size, distance from downtown Phoenix, and number of visitors to the entire park or National Forest (Table 1).

All the study sites had vegetation typical of the Arizona Uplands subdivision of the Sonoran Desert (Brown et al. 1998) including low lying trees such as *Parkinsonia microphylla* (palo verde), thorny shrubs such as *Ambrosia deltoidea* (bursage), *Larrea tridentata* (creosote bush), and *Encelia farinosa* (brittlebush); and cacti such as *Carnegiea gigantea* (saguaro), *Ferocactus cylindraceus* (barrel cactus), *Echinocereus engelmannii* (hedgehog cactus), *Fouquieria splendens* (ocotillo), *Cylindropuntia acanthocarpa* (buckhorn cholla), *Cylindropuntia arbuscula*, and *Cylindropuntia bigelovii* (teddybear cholla). Trees, shrubs and succulents that were identified at each of the sampling sites as part of the CAP LTER Survey 200 project are listed in Appendix A.

Soil properties data for the four study sites (Table 2) was accessed from the CAP LTER database (Grimm 2005). Data on monthly mean rainfall and temperature (Table 3 and Table 4 respectively) were accessed from the closest weather station to each site (Flood Control District of Maricopa County 2009).

Fig. 2 A-D Images of each of the four study sites. **A** Site U131. **B** Site U201. **C** Site AD101. **D** Site AF141.

Table 1 Information about study sites including location, size, visitors per entire park, elevation, slope and aspect.

SITES	Distance from Downtown Phoenix (km)	Visitors per year to the entire park or National Forest	Size (km^2)	Elevation (m)	Slope (degrees)	Aspect	Coordinates
U131[ad]	16.6	NA	12.14	525	26	0	33°35'47"N, 112°04'50"W
U201[ad]	9.7	3 million	66.73	740	10	0	33°20'10"N, 112°03'24"W
AF141[bd]	67.8	5.8 million	12,000	482	0	0	33°32'05"N, 111°35'45"W
AD101[cd]	64.4	76,500	85.38	537	4	135	33°40'37"N, 111°42'40"W

NA= Not available; Aspect=0=North

Sources: [a] City of Phoenix (2009), [b] Tonto National Forest (2009), [c] Maricopa County Parks and Recreation Dept. (2009), and [d] Grimm (2005).

Table 2 Soil properties for study sites

	Soil Texture				Soil Chemistry					
Sites	Sand %	Silt %	Clay %	Soil type	pH	Conductivity (milli Siemens)	Total Carbon %	Total Nitrogen %	Phosphorus (mg/kg)	Soil Organic Matter %
U131	43	45	12	Loam	7.53	0.298	1.253	0.105	9.75	4.80
U201	32	58	10	Silt loam	8.09	0.393	0.964	0.098	5.14	2.33
AF141	24	71	5	Silt loam	7.38	0.141	0.605	0.055	13.20	2.48
AD101	60	15	25	Sandy clay loam	8.14	0.331	2.131	0.051	7.44	3.02

Source: Grimm (2005)

Table 3 Monthly mean rainfall in mm at the nearest weather station to each study site during the summer monsoon and winter rainfall prior to sampling time.

Sites	Jun 2007	Jul 2007	Aug 2007	Sept 2007	Oct 2007	Nov 2007	Dec 2007	Jan 2008	Feb 2008	Cumulative rainfall
U131	0.0	22.1	0.0	5.1	0.0	33.0	20.1	41.9	10.9	133.1
U201	0.0	26.9	7.9	6.1	4.1	39.1	31.0	35.1	7.9	158.1
AF141	0.0	19.1	5.1	2.0	2.0	38.1	53.1	55.9	24.9	200.2
AD101	0.0	75.9	6.1	2.0	0.0	56.9	83.1	112.0	21.1	357.1

Source: Flood Control District of Maricopa County (2009)

Table 4 Monthly maximum, mean and minimum temperatures (°C) at the nearest weather station to each study site for the year prior to sampling.

	U131			U201			AF141			AD101		
Month	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min
Mar 2007	38.3	20.0	0.0	35.6	20.0	5.0	37.8	20.0	2.2	36.7	18.9	0.0
Apr 2007	37.8	21.7	6.1	36.7	22.2	7.8	37.2	22.2	7.8	38.3	21.1	7.2
May 2007	39.4	26.7	11.1	40.0	28.9	15.0	39.4	28.3	12.2	39.4	27.8	12.2
Jun 2007	44.4	32.8	15.6	43.3	33.9	20.0	43.3	32.8	17.2	43.3	32.2	16.7
Jul 2007	46.7	35.0	21.7	46.1	34.4	23.9	45.0	33.9	22.2	44.4	33.9	22.8
Aug 2007	46.1	34.4	24.4	44.4	34.4	23.3	44.4	33.9	23.3	44.4	33.9	23.3
Sep 2007	43.3	29.4	12.2	42.2	31.1	20.6	42.8	30.6	16.7	43.3	30.0	15.0
Oct 2007	35.6	22.8	7.8	35.6	25.6	14.4	36.1	25.0	12.8	35.0	23.3	11.1
Nov 2007	33.9	18.3	1.7	32.2	21.7	8.9	33.9	21.1	6.1	33.9	19.4	4.4
Dec 2007	25.0	9.4	-2.2	23.9	11.7	2.8	25.0	11.1	0.6	26.7	9.4	-0.6
Jan 2008	21.1	10.6	-2.8	20.6	12.2	2.2	22.2	11.7	1.7	22.2	10.6	0.6
Feb 2008	28.3	11.7	-1.1	26.7	14.4	3.9	27.8	13.3	0.6	27.8	12.2	-0.6

Source: Flood Control District of Maricopa County (2009)

During the winter 2007, permission was obtained to collect soil samples at each site and the collection of soil samples at these sites occurred between January to mid February 2008. In order to select plants for soil sampling, a 50m transect (in a general east to west direction) was centered at the GPS-located center point for each site. At 5m intervals along the transect, the nearest living woody and succulent plant was selected and soil collected from the rhizosphere at the base of each plant. Surface debris was removed and soil and roots were collected to a depth of approximately 10 cm with a metal trowel, which was rinsed with water and then with 70% ethanol between samples. Soil samples were collected from the root zone of 10 woody plants and 10 succulent plants (including cacti) at each site for a total of 80 samples (Appendix B lists plants sampled at each study site). All the samples were placed into self-sealing plastic bags and transported to ASU Polytechnic campus. Samples were stored at 4° C until analysis.

Root processing and assessment of root colonization

Root processing involved removing 40 to 50 fine (≤ 2mm width), fibrous, healthy appearing roots from each soil sample. Roots were washed with water and a commercial softener (Calgon™, Benckiser, CT) to remove soil particles, wrapped in mesh paper and placed into plastic tissue capsules. Roots were then fixed using a solution of 50% ethanol prior to staining procedures.

AM fungal colonization was assessed by staining roots in trypan blue using a modification of the method of Koske and Gemma (1989) with the potassium hydroxide (KOH) concentration adjusted for woody and succulent plant roots. Because succulent plant roots were thinner than woody plant roots, the concentration of KOH used was 1.5 % for the succulent plant roots and 4% for the woody plant roots. To assess the possible presence of DSE, double staining was performed with Sudan IV staining (Barrow and Aaltonen 2001) after staining with trypan blue; then roots were stored in acidic glycerol until preparation of slides. Approximately 30 root

segments of 1cm were mounted on slides by placing them horizontally across the slide with several drops of acidic glycerol solution, and covered with a cover slip. Slides were examined using a light microscope at 40X magnification. Percent root colonization was quantified following the magnified intersections method of McGonigle et al. (1990) by using a compound microscope fitted with an ocular crosshair. At each intersection of a root and the vertical axis of the crosshair, the root was analyzed for the process of AM fungal structures such as hyphae, vesicles, arbuscules, coils, colonization by DSE, colonization by other fungi or no colonization and the result recorded until at least 100 intersections were assessed.

Assessment of AM fungal diversity

A subsample of 250 cm^3 of each soil sample was mixed with 250 cm^3 of #12 and #20 silica sand (1:1) to set trap cultures that were grown in the greenhouse. Trap cultures were established following the protocol reported by Stutz and Morton (1996). This technique has been used to promote AM fungal spore production in desert soils (Stutz and Morton 1996). Surface-sterilized 656 ml Deepots™ (Stuewe and Sons, OR) were placed in benches with a mixture of planting media 1:1:2 of sterilized silica sand #20 and #12 and sample soil per each Deepot. Around 40 to 50 surface-sterilized Sudan grass (*Sorghum sudanese*) seeds were added to the surface of the Deepots and covered to a depth of 1cm with wet silica sand #12. Trap cultures were grown in the greenhouse at ASU Polytechnic campus and watered as needed over the course of 3 months until Sudan grass flowering and subsequent dry down. After drying down, stems were harvested. New surface-sterilized Sudan grass seeds were placed into the Deepots and covered by wet silica sand #12. The second generation of trap cultures was grown and watered as needed during 3 months until Sudan grass flowering. ParEX™ (Vigoro Industries, Il) slow release nitrogen fertilizer (20-

0-20 in IBDU) was top dressed once and biological control (Gnatrol™, Valent Products, CA) applications for fungus gnats were applied as a drench as needed.

After 2 generations of trap cultures, watering was stopped and cultures dried down. Plant tops were clipped and cultures removed and placed in self-closing plastic bags and stored at 4° C until analysis. Spore analysis was done with a 100 cm^3 subsample of the trap cultures soil by using wet sieving and sucrose density gradient centrifugation (Daniels and Skipper 1982). Spores were washed into a petri dish for examination with a stereomicroscope. Healthy spores were separated into different morphotypes based on shape, color, size, surface conditions, spore contents and no evidence of parasitism. Spores were mounted on slides in polyvinyl alcohol lactic acid-glycerol (PVLG) (Koske and Tessier 1983) and PVLG mixed 1:1 (v/v) with Melzer's reagent to be compared with voucher specimens and descriptions from the International Culture Collection of Arbuscular and Vesicular-Arbuscular Mycorrhizal Fungi (INVAM) (Morton et al. 1993). Species richness was calculated as the numbers of AM fungal species present at each site.

Statistical analysis

Root colonization data was analyzed using ANOVA of a two factor factorial with site type (desert or urban) and plant type (woody or succulent) as factors by using R version 2.7.2 (The R Foundation for Statistical Computing, 2008). Root colonization percentage was square root transformed to approximate normality. An alpha probability value of 0.05 was assumed for all statistical analyses. To assess the level of fungal colonization, means and the standard error of means were calculated using Excel®.

AM fungal species from soil and second-generation trap cultures were used to determine species richness and composition. Sampling effort curves were generated using EstimateS 8.0 program (Colwell 2006; Colwell et al. 2004). Relative frequency was used as indicator of

dominance since spore abundance in trap cultures is likely to provide a measurement of natural conditions and lacks ecological significance. Relative frequency was determined for each AM fungal species for each factor (site type and plant type) as the number of detections divided by the total number of samples (40 samples). Differences in the number of AM fungal species/sample was analyzed using ANOVA of a two factor factorial with site type (desert or urban) and plant type (woody and succulent) as factors by using R version 2.7.2. Means and standard errors of means were calculated by Excel®. AM fungal species composition was compared between sites using Sorenson's coefficient of similarity with species present/absence data and following the equation:

$$QS = (2C)/(A+B)$$

where:

QS= Sorenson's coefficient of similarity

A = Number of species at site X

B = Number of species at site Y

C = Number of species common to both (X & Y)

Results

Roots of all plants were colonized by AM fungi including typical structures such as arbuscules (Fig. 3A) and vesicles (Fig. 3B). There was a highly significant difference in total root colonization by AM fungi between urban desert preserves and surrounding deserts (Table 5). Total root colonization by AM fungi was over two times higher in plants from surrounding deserts compared to urban desert preserves (Fig. 4). While mean total root colonization by AM fungi was lower in succulent plants in comparison to woody plants, this difference was not significant (Table 5, Fig. 5). The interaction among sites and plant type was not found to be statistically significant.

There were highly significant differences in root colonization by hyphae and vesicles and significant differences by arbuscules and hyphal coils between plants sampled in urban desert preserves in comparison to plants from the surrounding deserts with greater percentage of the roots colonized by these structures in plants from the surrounding deserts (Table 5, Fig. 6). Root colonization by vesicles was significantly higher in woody plants when compared to succulent plants (Table 5, Fig. 7). No significant interactions among factors were found.

DSE colonization was detected as stained lipid bodies in vacuoles of fungal hyphae in the root cortex (Fig. 8A), in some cases in the vascular tissue, and as microsclerotia in the root cortex (Fig. 8B). Total root colonization by DSE (Appendix B) was not significantly different in plants from surrounding deserts compared to urban desert preserves (Table 5, Fig. 4). However, there was a significant difference in root colonization by DSE between succulent and woody plants with a higher percentage of roots colonized by DSE in succulent plants than in woody plants (Fig. 5). The interaction between sites and plant type was not found significant.

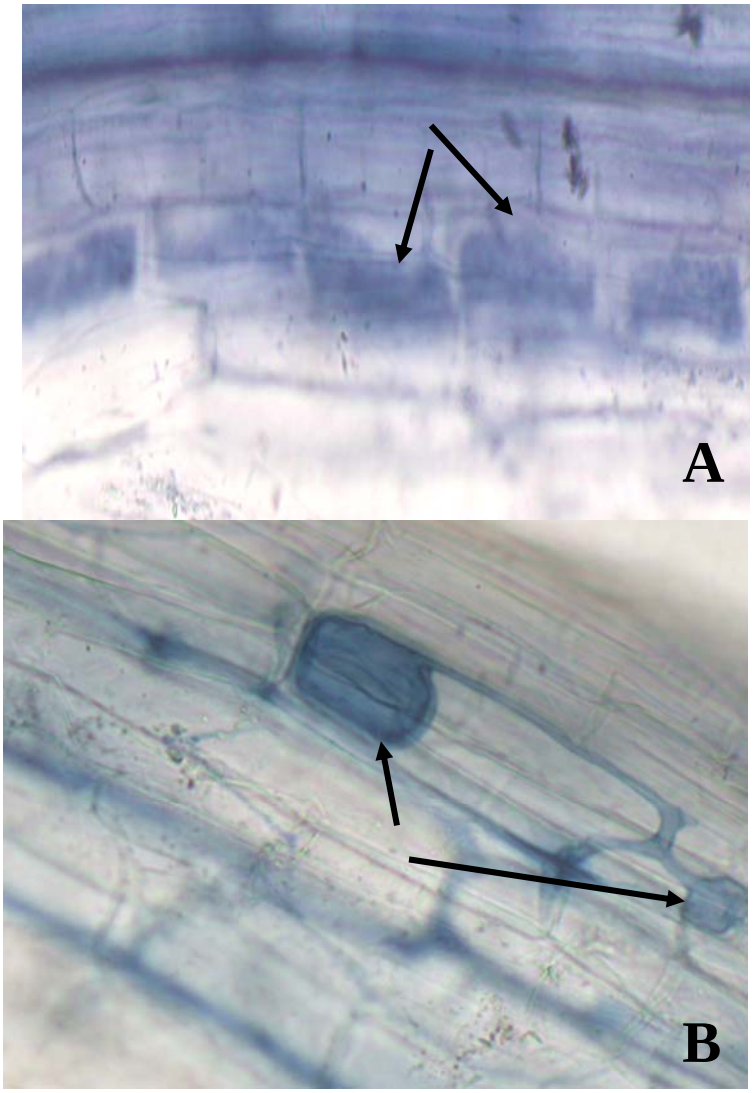

Fig. 3 A-B AM colonization of *Ambrosia deltoidea* roots. **A**rrows point to AM fungal structures. **A** Arbuscules found at root cortex. **B** Vesicles and hyphae found at root cortex.

Table 5 Significance values for factors in a two factor factorial ANOVA analysis for fungal root colonization by AM, DSE and other fungi and AM fungal species

	Factors	F	p-value
FUNGAL ROOT COLONIZATION.			
Total AM fungal root colonization	Sites***	32.29	<0.001
	Plant	2.39	0.127
	Sites x Plant	0.66	0.418
AM fungal structure			
Hyphae	Sites***	28.70	<0.001
	Plant	0.65	0.422
	Sites x Plant	1.07	0.305
Vesicles	Sites***	29.40	<0.001
	Plant**	10.20	0.002
	Sites x Plant	1.00	0.320
Arbuscules and hyphal coils	Sites*	5.19	0.026
	Plant	0.94	0.337
	Sites x Plant	1.31	0.255
DSE	Sites	0.41	0.522
	Plant**	8.36	0.005
	Sites x Plant	1.01	0.317
Other fungi	Sites	2.62	0.110
	Plant	0.34	0.564
	Sites x Plant	0.02	0.886
AM SPECIES IDENTIFICATION			
#AM fungal species/sample	Sites	1.21	0.274
	Plant	1.95	0.167
	Sites x Plant	0.05	0.826

*p<0.05, **p<0.01, ***p<0.001

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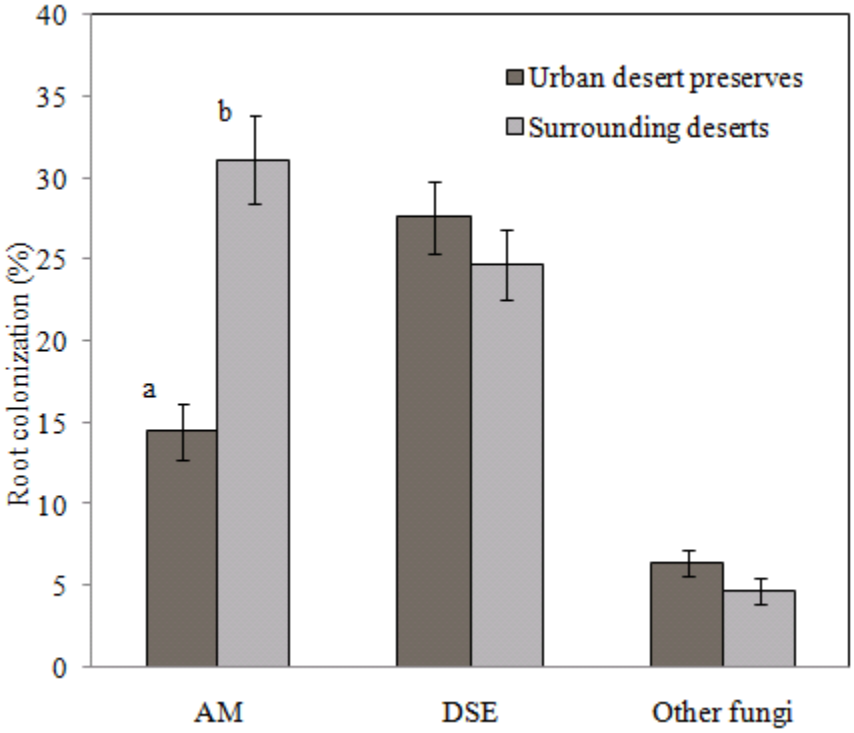

Fig. 4 Fungal root colonization by AM, DSE and other fungi in plants collected at urban desert preserves (sites U131 and U201) and surrounding deserts (sites AF141 and AD101). Data are means and standard errors. Different letters indicate significant differences.

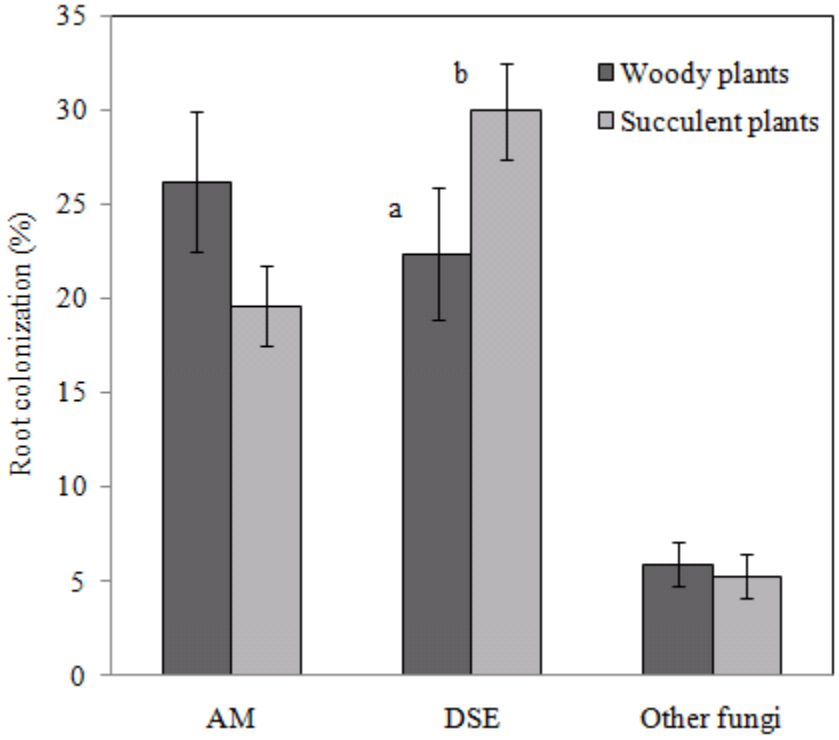

Fig. 5 Fungal root colonization by type of plants collected at urban desert preserves (sites U131 and U201) and surrounding deserts (sites AF141 and AD101). Data are means and standard errors. Different letters indicate significant differences.

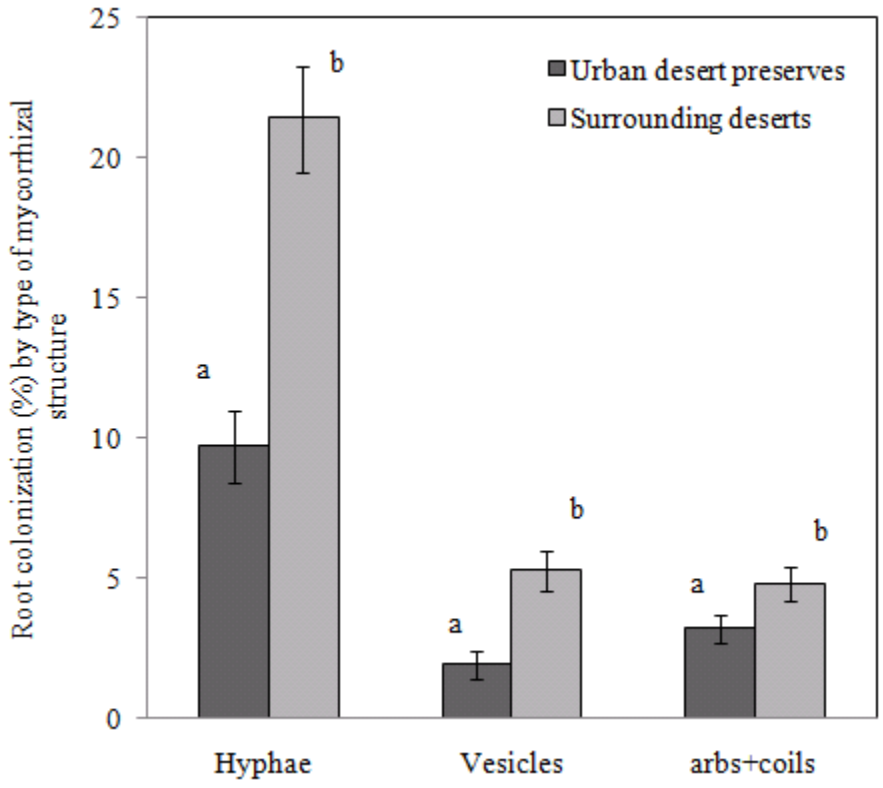

Fig. 6 Formation of hyphae, vesicles, arbuscules and hyphal coils in plant roots collected at urban desert preserves (sites U131 and U201) and surrounding deserts (sites AF141 and AD101). Data are means and standard errors. Different letters indicate significant differences.

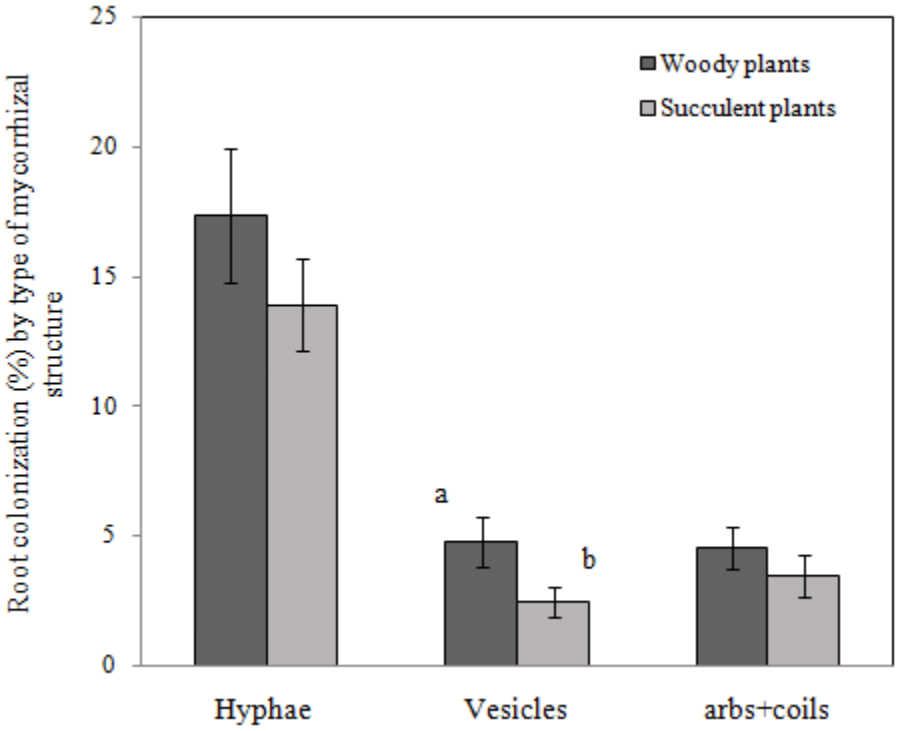

Fig. 7 Formation of hyphae, vesicles, arbuscules and hyphal coils in woody and succulent plant roots collected at urban desert preserves (sites U131 and U201) and surrounding deserts (sites AF141 and AD101). Data are means and standard errors. Different letters indicate significant differences.

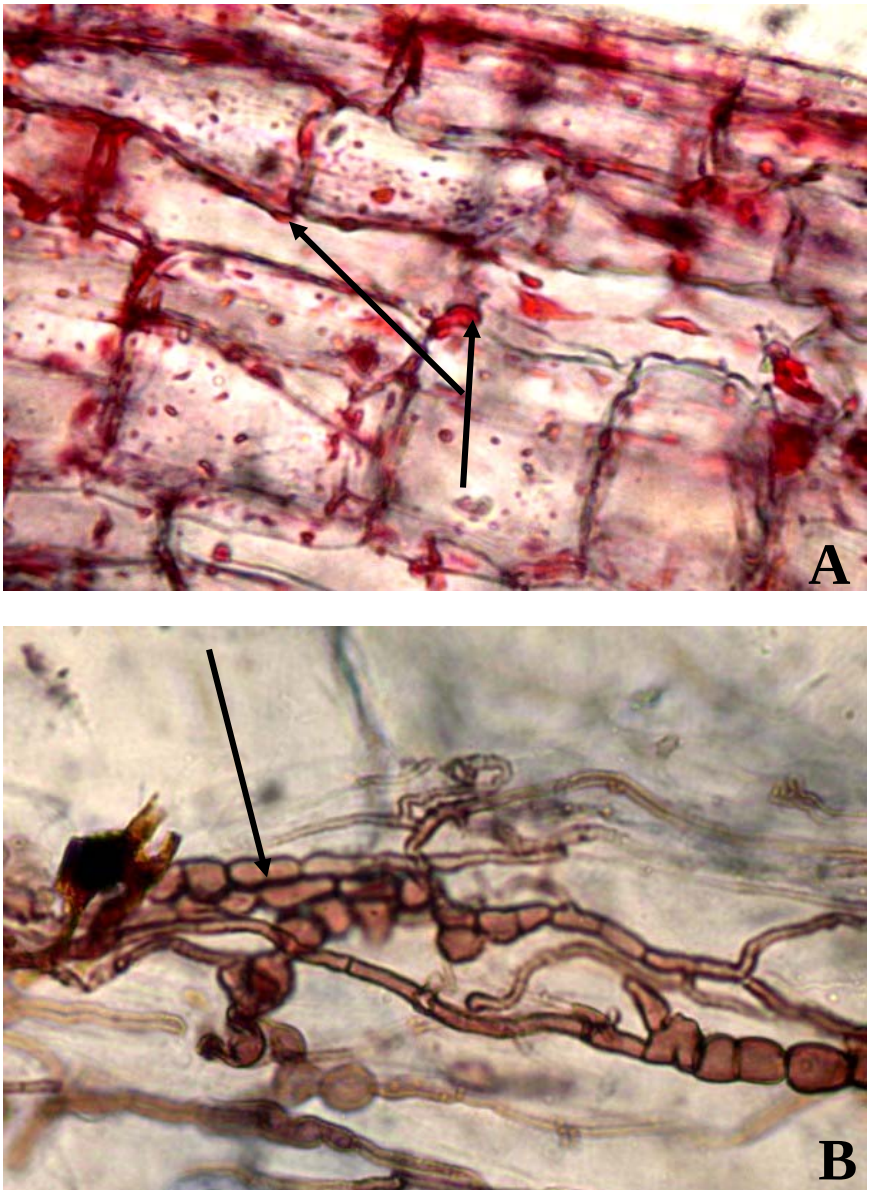

Fig.8 A-B DSE root colonization. See arrows. **A** DSE in root cortex of succulent plant roots of *Carnegiea gigantea* that stained red with Sudan IV. (Right) **B** Microsclerotia from succulent plant roots of *Echinocereus engelmannii.*

Other fungi were also observed including the presence of non-mycorrhizal septate hyphae and in some cases water molds. Total root colonization by other fungi was not significantly different between surrounding deserts and urban desert preserves (Table 5, Fig. 4). There were no significant differences in root colonization by other fungi between succulent and woody plants, and no significant interaction between factors was found.

There was a total of twenty-two species of AM fungi detected at the four study sites (the two urban desert preserves located in the Phoenix metropolitan area and two Sonoran Desert sites) (Table 6), including two undescribed *Glomus* morphotypes, *Glomus* sp. AZ 112 and *Glomus* sp. AZ 123 that had previously been detected in the Sonoran Desert (Stutz et al. 2000); and two new *Acaulospora* morphotypes that were assigned a number based on the sample location where they were first detected (*Acaulospora* sp. AF141-3S and A*caulospora* sp. AF141-5W) (Fig. 9).

The total number of AM fungal species detected at the surrounding desert sites was greater than at the urban desert preserves (Table 6). Sampling effort curve suggests that most species at the urban desert preserves and surrounding deserts were detected (curves reached asymptote) and that the total numbers of AM fungal species are higher in surrounding desert sites in comparison to urban desert preserves (Fig.10).

The number of AM fungal species/sample was not significantly different between urban desert preserves and surrounding desert sites (Table 5) ranging from 2 to 8 species/sample with a mean of 4.38 $\pm$0.24 species/sample for urban desert preserves and of 4.75$\pm$0.24 species/sample for surrounding desert sites. There were also no significant differences for the number of AM fungal species/sample detected in samples collected from succulent and woody

Table 6 AM fungal species observed in soil and trap cultures from urban desert preserves and surrounding deserts from Phoenix, Arizona.

Family	Genus species	Authority	Urban	Desert
Archaeosporaceae	*Archaeospora trappei*	(Ames & Linderman) Morton & Redecker emend. Spain	X	X
Acaulosporaceae	*Acaulospora delicata*	Walker, Pfeiffer and Bloss	−	X
	Acaulospora mellea	Schenck, Spain, Sieverding & Howeler	−	X
	Acaulospora morrowiae	Spain & Schenck	−	X
	Acaulospora AF141-3S	Undescribed	−	X
	Acaulospora AF141-5W	Undescribed	−	X
	Entrosphora infrequens	(Hall) Ames & Schneider	−	X
Diversisporaceae	*Diversispora spurca*	(Pfeiff., Walker & Bloss) Walker & Schüβler	X	X
Glomaceae	*Glomus claroideum*	Schenck & Smith emend Walker & Vestberg	X	X
	Glomus eburneum	Kennedy, Stutz & Morton	X	X
	Glomus etunicatum	Becker & Gerd.	X	X
	Glomus fasciculatum	(Thaxter) Gerd. & Trappe emend. Walker & Koske	X	X
	Glomus geosporum	Walker	X	−
	Glomus intraradices	Schenck & Smith	X	X
	Glomus luteum	Kennedy, Stutz & Morton	X	X
	Glomus macrocarpum	Tulasne & Tulasne	X	X
	Glomus microaggregatum	Koske, Gemma & Olexia	X	X
	Glomus mosseae	(Nicolson & Gerd.) Gerd. & Trappe	X	X
	Glomus sinuosum	(Gerd. & Bakshi) Almeida & Schenck	X	−
	Glomus sp. AZ 112	Undescribed	X	X
	Glomus sp. AZ 123	Undescribed	X	X
Paraglomeraceae	*Paraglomus occultum*	(Walker) Morton & Redecker	X	X
		Total number of species detected	16	20

X=Species presence, − =Species absence

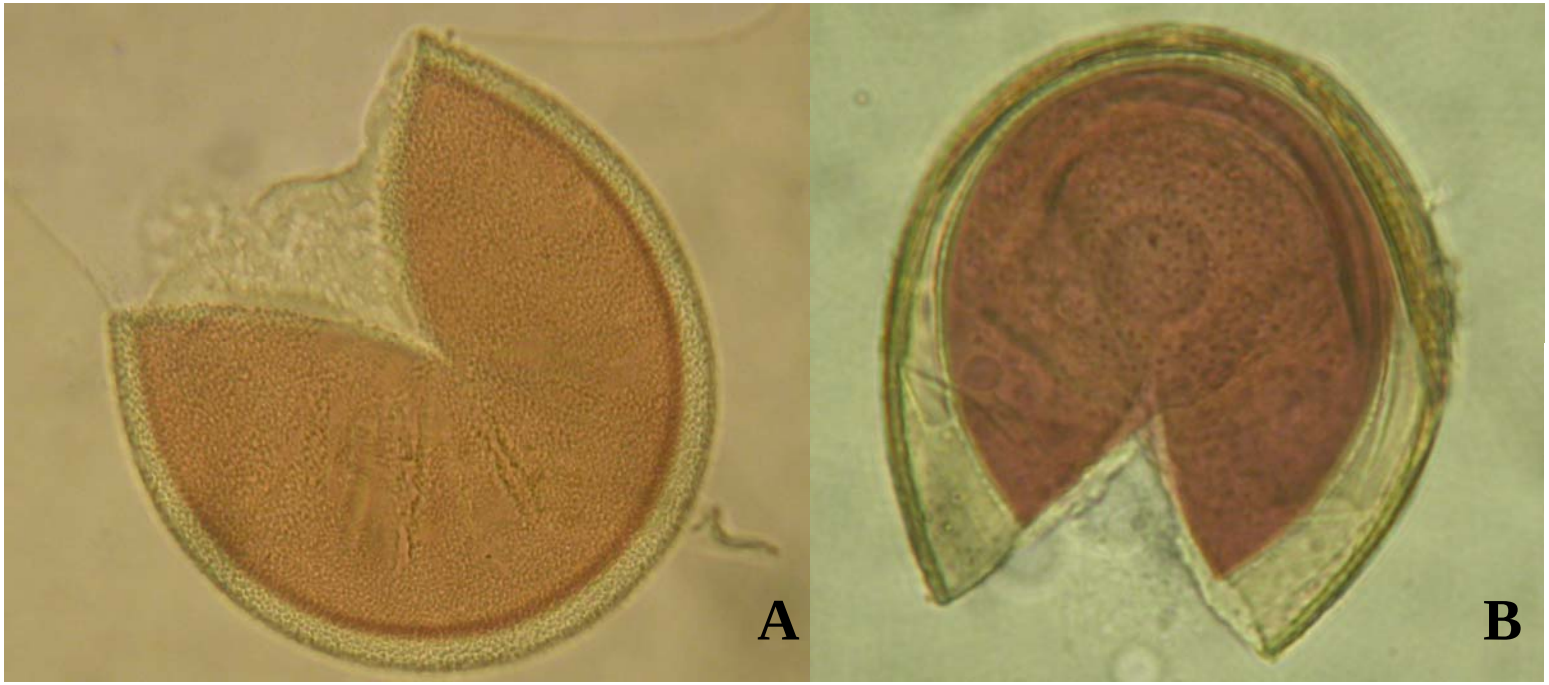

Fig. 9 A-B Images of the new *Acaulospora* species found at one of the surrounding desert sites. **A** *Acaulospora* sp. AF141-3S, mean diameter 184.2 µm, spore was collected from trap culture of *Cylindropuntia leptocaulis.* **B** *Acaulospora* sp. AF141-5W, actual diameter 75 µm, spore was collected from trap culture of *Ambrosia deltoidea.* Both microscopic images were taken at 40X.

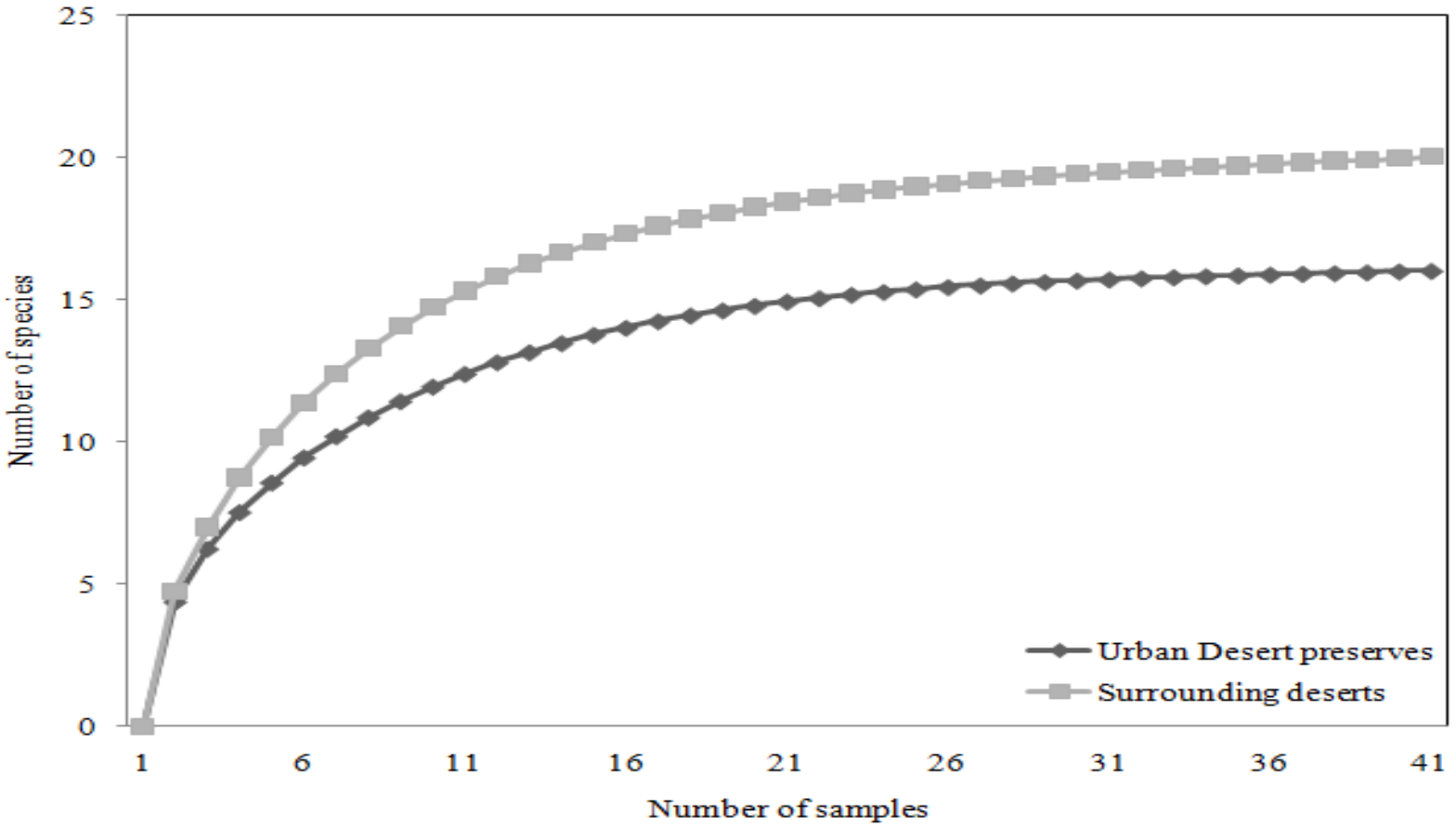

Fig. 10 Sampling effort curves for detecting the number of AM fungal species.

plants and no significant interaction. The greatest number of AM fungal species/sample was associated with *Ambrosia deltoidea* (8 species) at urban desert preserve sites and with *Ambrosia deltoidea* and *Larrea tridentata* at desert sites (8 species) (Appendix B).

About 70% of the AM fungal species were detected at both urban desert preserves and surrounding desert sites (Table 6). *G. intraradices* and *G. mosseae* were the most frequently detected species and were observed in either soil or trap cultures of over 90% of samples. AM fungal species from the family *Acaulosporaceae, A.delicata, A. mellea, A. morrowiae, Acaulospora.* sp. AF141-3S*, Acaulospora* sp. AF141-5W and *E. infrequens*; were only detected at the surrounding desert sites. Two species, *G. geosporum* and *G. sinuosum*, were only detected at the urban preserves sites.

When comparisons were made between the relative frequency of AM fungal species at urban desert preserves and surrounding desert sites (Fig. 11), there was little difference between the frequency of detection of *G. intraradices* and *G. mosseae.* Three commonly detected species, *G. etunicatum, G. microaggregatum* and *Glomus* sp. AZ 123, were detected at higher relative frequencies in samples collected from urban desert preserves than in those collected from the surrounding deserts. Several rarer species including *G. macrocarpum, G. luteum, G. eburneum* and *G. fasciculatum* were detected at higher frequencies in samples from the surrounding deserts than in those from urban desert preserves.

When comparisons were made between the relative frequencies of AM fungi associated with woody and succulent plants, there were some similarities to the patterns observed for urban and desert sites (Fig. 12). *G. intraradices* and *G. mosseae* were the most frequently detected species with relative frequencies over 90% for both succulent plants and woody plants. Two

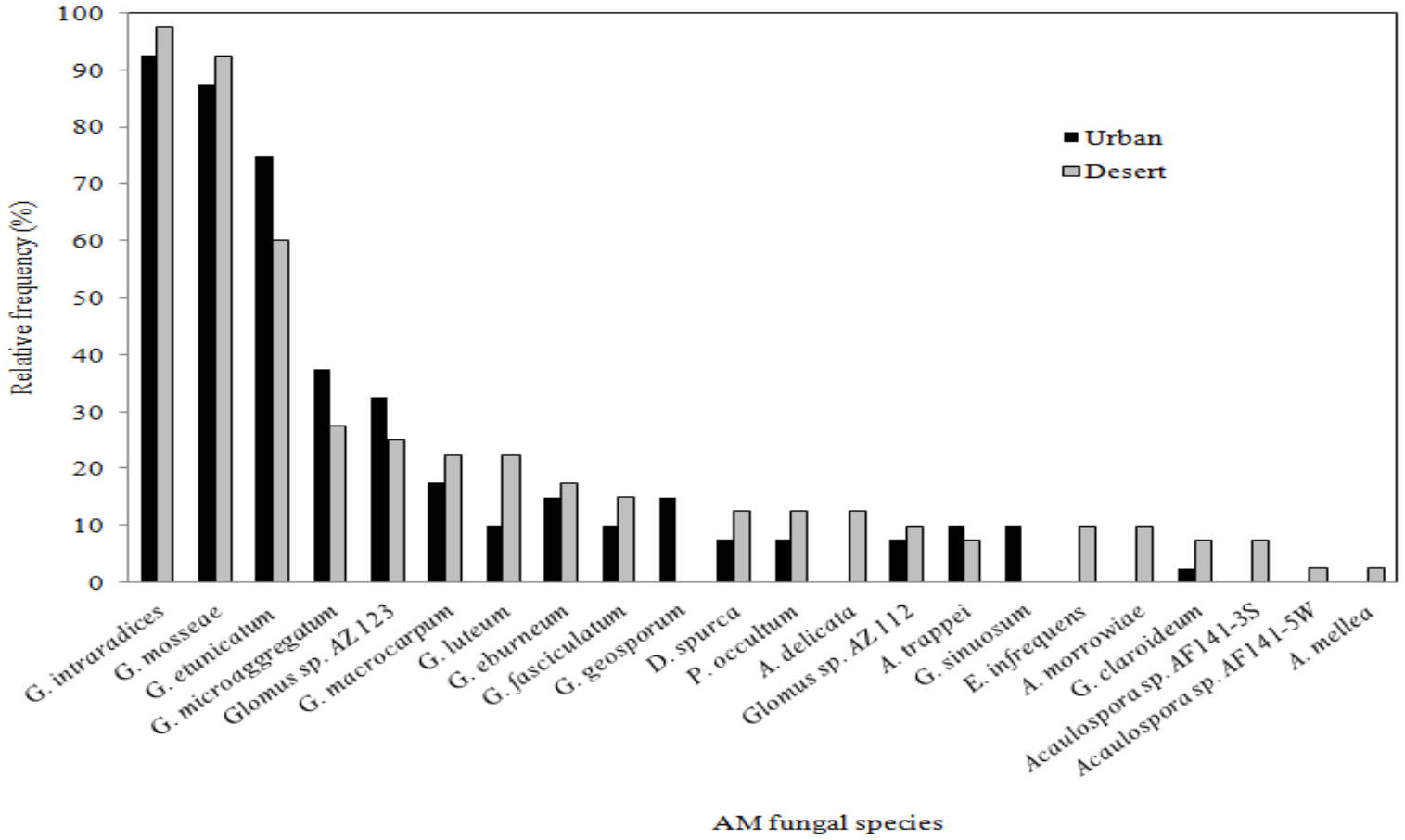

Fig.11 Relative frequency of AM fungal species detected at the urban and desert sites.

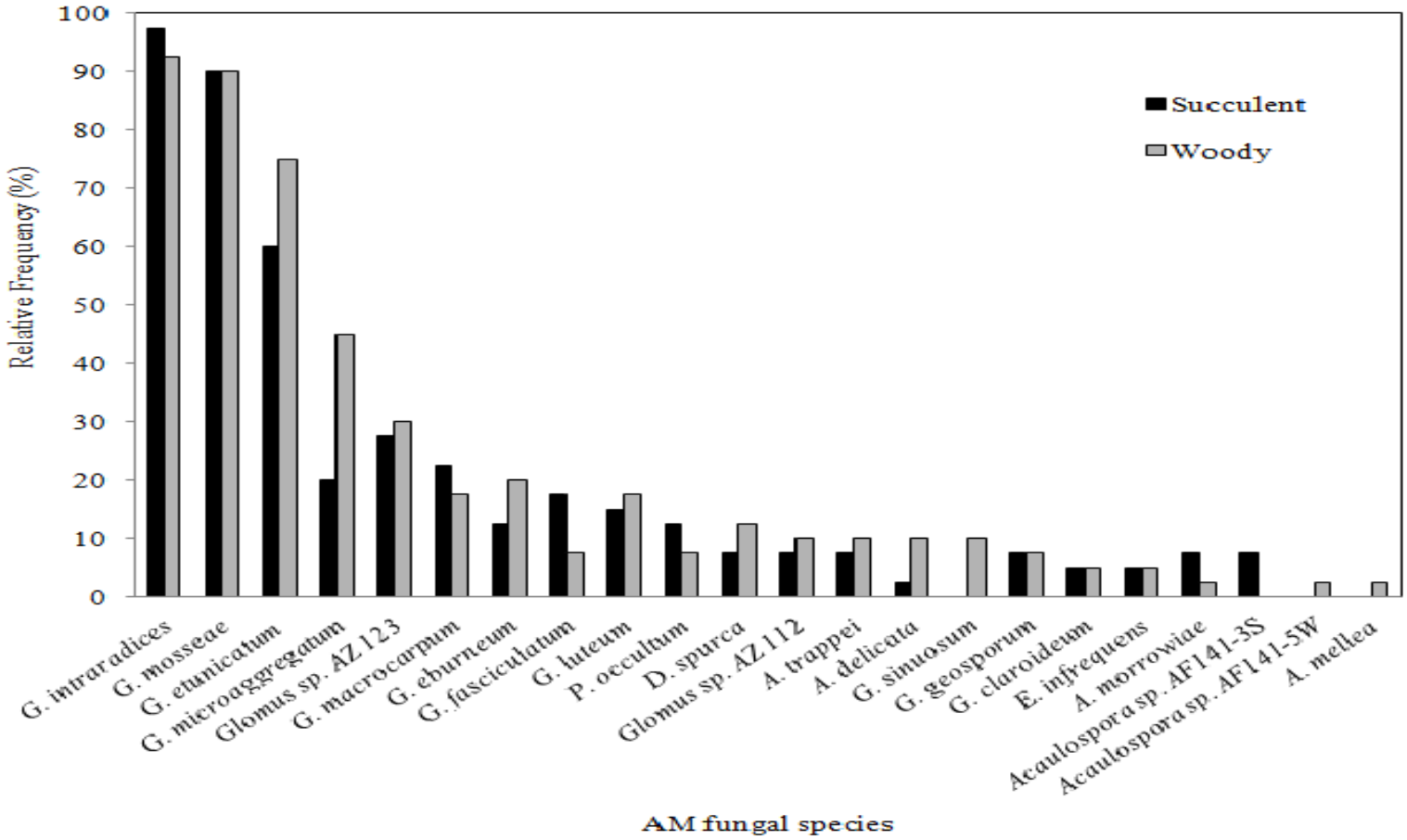

Fig. 12 Relative frequency of AM fungal species detected for the succulent and woody plants.

common species, *G. etunicatum* and *G. microaggregatum,* were more frequently detected in samples collected from woody plants in comparison to succulent plants. There was little difference in the frequency of detection in samples collected from woody and succulent plants for most of the rarer AM fungal species, although *G. sinuosum, Acaulospora.* sp. AF141-5W and *A. mellea* were only detected in samples collected from woody plants and *Acaulospora* sp. AF141-3S was only detected in succulent plants.

AM fungal species richness (AM species per site) and composition varied between the four sampling sites (Fig. 13). AM fungal species richness was greatest at desert sites (AF141 and AD101) and lowest at urban desert preserve sites (U131 and U201). Species richness had a mean and standard error of 17$\pm$1 at the desert sites and of 12.5$\pm$1.5 at the urban desert preserves. Although members of the family *Glomaceae* dominated all study sites (Fig. 13), it was notable that members of the family *Acaulosporaceae* were the second most commonly detected group at desert sites but were not detected at urban desert preserve sites. In addition, one member of the family *Paraglomeraceae* (*P. occultum*) was detected at both surrounding desert sites and at one urban preserve site (U131) and one member of the family *Diversisporaceae* (*D. spurca)* was detected at both surrounding desert sites and at one urban preserve site (U201). One member of the family *Archaeosporaceae* (*A. trappei*) was detected at all study sites. *G. geosporum* and *G. sinuosum* were only detected at an urban desert preserve (site U201). Rare species that were only found at the surrounding desert sites included *A. mellea* and *E. infrequens,* (found at site AD101); *Acaulospora* sp. AF141-3S and *Acaulospora* sp. AF141-5W (found at site AF141); and *A. morrowiae* and *A. delicata* (found at sites AD101 and AF141).

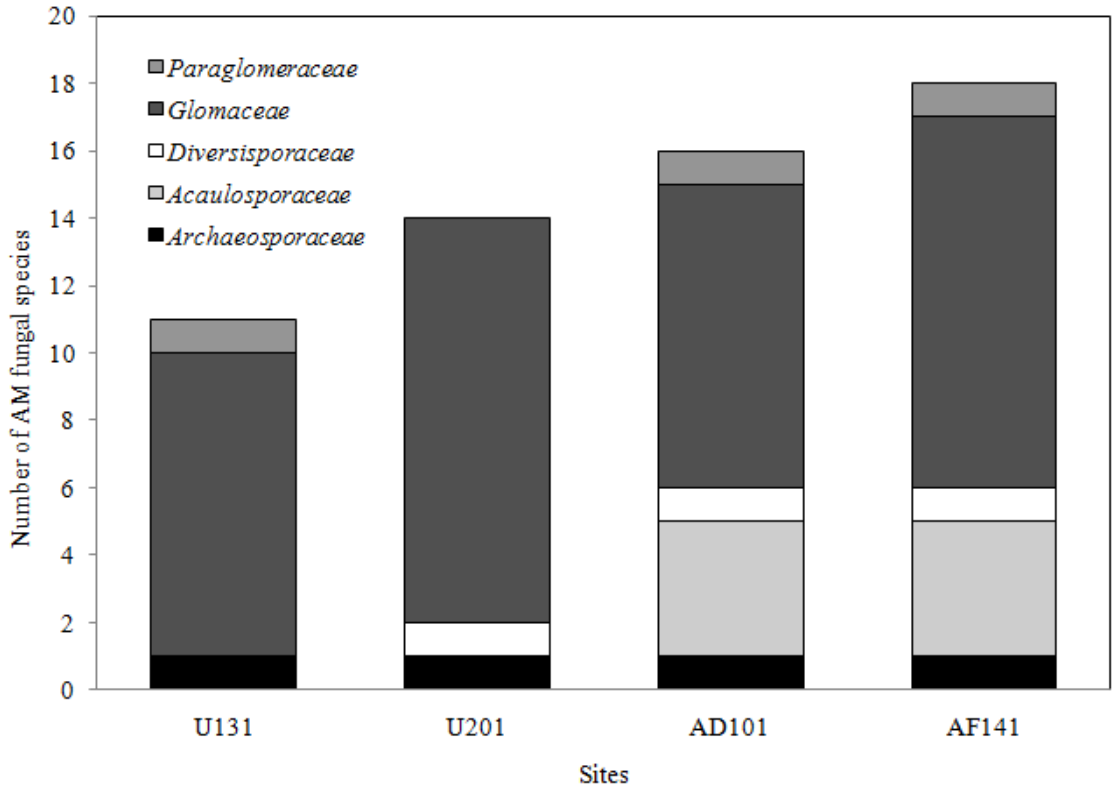

Fig. 13 Proportion of detected AM fungal species by family at each sampling site.

Sorenson's coefficient of similarity (Table 7) confirmed that the highest similarity was between the surrounding desert sites (sites AD101 and AF141). There was also a high similarity between an urban desert preserve and a surrounding desert (sites U131 and AD101 respectively) due to the fact that they shared mostly all detected species from the families *Glomaceae, Archaeosporaceae* and *Paraglomeraceae*. The two urban desert preserves (sites U131 and U201) had a similarity higher than 0.7.

Table 7 Sorenson's coefficient of similarity for AM fungal species composition detected at study sites. Values closer to 1.00 represent greatest similarity among sites.

Site	U131	U201	AD101	AF141
U131		0.72	0.82	0.76
U201			0.67	0.75
AD101				0.82

Discussion

Natural preserves have been used as instruments for species conservation in many ecosystems. McKinney (2002) made a call for the use of remnant natural habitats in urban areas to preserve native species. He pointed out that preserving remnant natural habitat in urban areas is the cheapest way to safeguard the long term survival of native species; however, he also noted that remnants are exposed to non-native species and predators that can greatly decrease the ability of remnants to protect native species. Anthropogenic activities in urban ecosystems can generate negative effects such as soil disturbance, increases in atmospheric nitrogen deposition, air and soil pollutants and higher average ambient temperature (urban heat island effect) (Pickett et al. 2001; Grimm and Redman 2004) that may also impact diversity including that of AM and DSE fungi. Hence, the importance of empirical studies such as the current study to determine the efficacy of using urban desert preserves to safeguard AM and DSE fungal species.

The results of this study found that urban desert preserves had many similarities with regard to AM and DSE fungi with surrounding desert areas but some key differences. As predicted in the initial hypothesis, total AM fungal colonization levels were lower in urban desert preserves. Lower levels of colonization in desert preserves may be a result of negative effects associated with urbanization (McKinney 2002; McKinney 2006), but there are other factors that differed between the sites selected that could have resulted in decreases in colonization. According to Abbot and Robson (1991), AM fungal colonization levels can vary with several environmental variables such as soil type and depth, nutrient levels, season and vegetation. Even though the study sites were selected based on similar vegetation type; there were slight differences between sites in the species of plants that were sampled. Data from the closest

weather station to each site revealed similar air temperatures (Table 4) that might exclude an urban heat island effect in the urban preserves; but this data also indicated that rainfall amounts at the surrounding desert sites were higher than at the urban desert preserves especially during the winter months that directly proceeded sampling (Table 3). Soil moisture levels have been shown to influence AM root colonization levels especially in arid and semi-arid regions (Jacobson 1997; O'Connor et al. 2001). Finally, there were some differences in soil nutrients at each site (Table 2) particularly total nitrogen percentages which were higher at the urban desert preserves than at the surrounding deserts. Higher nitrogen levels have been linked to lower levels of AM fungal root colonization (Johnson 1993) and may account for the lower levels of colonization observed at urban desert preserves. Further research is required to investigate the relationship between AM root colonization and these factors to elucidate the driving forces behind the differences in AM fungal root colonization observed between urban desert preserves and peripheral deserts.

Another factor that can effect AM fungal colonization is seasonality. For example, Titus et al. (2002) and Apple et al. (2005) found that AM fungal colonization of Mojave Desert plants was affected by seasonality. Titus et al. (2002) observed that the percentage of hyphae and vesicles decreased from spring to autumn, while arbuscules percentage increased in some species during this time. Although this current project provides preliminary indications that AM fungal colonization differs between urban desert preserves and surrounding deserts, future research is needed to see if these differences occur under different seasonal conditions.

AM fungi have shown to promote the growth of plants from arid ecosystems (Requena et al. 2001) by assisting plant survival under stress conditions such as drought and high temperatures. Because of these benefits, the differences observed in this study in root colonization between urban desert preserves and surrounding deserts could have impacts on the

survival of native plants. AM fungi have also been demonstrated to play a crucial role in plant biodiversity and ecosystem productivity and variability (van der Heijden et al. 1998). In the current study, there was no significant interactive effect between site and plant type indicating that colonization in woody plants and succulent plants were not differentially impacted by factors at the urban sites.

Another result of interest is that roots of all native desert plants were colonized by DSE. This is the first report of the presence of DSE in the roots of many of the succulent species and some of the woody plant species sampled. In addition, colonization by DSE fungi was found to be higher in roots of succulent plants in comparison to woody plants although there were no significant differences in colonization levels between urban preserves and surrounding deserts. Results from this study provide some evidence that higher levels of AM fungal colonization are linked to lower levels of DSE colonization. The site with the highest AM fungal colonization, site AD101, was the site with the lowest DSE colonization. In addition, roots of succulent plants had higher mean levels of DSE colonization and lower levels of AM fungal colonization than woody plants. These results may indicate a competition for the host photosynthates between AM fungi and DSE. Medina-Roldan et al. (2008) found that DSE and AM fungi coexisted on *Bouteloua gracilis* roots from the semiarid grasslands in Mexico. Since DSE colonization was four times higher than AM fungal colonization, Medina-Roldan et al. (2008) suggested that a competition for resources is controlling the fungal colonization of roots. While the current study provided an insight to the possible competition between AM fungi and DSE, further research is necessary to verify it.

This current study also found differences and similarities in AM fungal community structure between urban desert preserves and surrounding desert areas. As hypothesized, the total

number of AM fungal species detected was lower in urban desert preserves than in surrounding deserts. While the difference was not great (16 species detected in urban desert preserves versus 20 in surrounding deserts), species richness was also greater at the two desert sites in comparison to urban preserve sites. Several other groups (plants, birds, butterflies, insects and mammals) have also demonstrated a decrease in species richness at the urban cores (McKinney 2002). However, as suggested by Picket et al. (2008), biodiversity can also be high at urban ecosystems and contains valuable species. In the case of AM fungal biodiversity, Bills and Stutz (2009) reported a greater total number of AM fungal species and species richness at desert sites than at urban sites as the current study showed. Nevertheless, the urban sampling sites selected by Bills and Stutz (2009) were mostly residential sites and desert sites included both urban desert remnant sites and sites in the desert surrounding Phoenix.

Urban desert preserves were similar to surrounding deserts with regard to the number of AM fungi detected/sample. These results differ from those previously reported (Stabler et al. 2001; Cousins et al. 2003; Bills and Stutz 2009) which found significantly lower numbers of AM fungal species/sample in urban sites in comparison to desert sites. One explanation for the contradictory findings could be that urban sites in these previous studies where not located in urban preserves but in residential and commercial areas.

Despite the differences between the number of AM fungal species detected in urban desert preserves and at surrounding deserts, there were many similarities in the species composition between urban desert preserves and surrounding deserts. There was an overlap of 70% in AM fungal species between urban desert preserves and surrounding deserts and the most frequently observed species in both were *G. intraradices* and *G. mosseae*. Members of the family *Glomaceae* were the predominate species in both urban desert preserves and surrounding deserts

which is similar to previous studies of AM fungal communities in arid environments (Jacobson 1997; Stutz et al. 2000; Cousins et al. 2003; Tao et al. 2004; Beauchamp et al. 2006; Shi et al. 2006; Bills and Stutz 2009) and from earlier studies of urban sites within the Phoenix metropolitan area (Stabler et al. 2001; Cousins et al. 2003; Whitcomb and Stutz 2007; Bills and Stutz 2009). Most of the species detected were those frequently reported for the Sonoran Desert (Stutz et al. 2000).

The most frequent observed species were *G. intraradices* and *G. mosseae*, with relative frequencies over 90% at both urban desert preserves and surrounding deserts. Bills and Stutz (2009) also found that the two main colonizers of desert and urban sites with indigenous plants were *G. intraradices* and *G. mosseae.* In the present study, *G. microaggregatum* was detected at higher frequencies at urban desert preserves than at the surrounding desert sites similar to the results of Cousins et al. (2003); however Bills and Stutz (2009) reported a higher occurrence of *G. microaggregatum* in desert sites. *G. luteum* was more frequently detected at surrounding deserts sites similar to the results of Bills and Stutz (2009) who found that *G. luteum* was detected at higher frequencies at desert sites. It was notable that *D. spurca* was one of the principal and commonly detected species in previous studies from urban and desert sites in Phoenix (Cousins et al. 2003; Bills and Stutz 2009) and in the current study had a relative frequency of less than 15%.

Although there were similarities in the AM fungal species composition of urban desert preserves and surrounding deserts, there were some significant differences. It is most noteworthy that species from the family *Acaulosporaceae* were completely absent at the urban desert preserve sites, but were the second most frequently observed group in desert sites. According to Sorenson's coefficient, the highest species similarity occurred between both surrounding deserts (sites AD101 and AF141) and between an urban desert preserve (site U131) and a surrounding

desert (site AD101). The similarity among desert sites appeared to be from a high degree of shared AM fungal species from all the families detected (*Glomaceae, Archaeosporaceae, Acaulosporaceae, Paraglomaceae* and *Diversisporaceae*). In contrast, the similarity between one urban desert preserve and one surrounding desert site was the result of sharing species mostly from the family *Glomaceae* (9 of the 13 species detected) and additional species from *Archaesporaceae* (1 species in common) and *Paraglomaceae* (1 species in common). Finally, Sorenson's coefficient of similarity calculated for the two urban desert preserves was relative high (>0.7) and appeared to be because both sites lacked AM fungal species from the family *Acaulosporaceae*, had one species in common from the family *Archaeosporaceae* and had many of the same species from the family *Glomaceae.*

One possible explanation for differences in species composition observed between urban preserves and surrounding deserts is that nitrogen levels at the two urban desert preserves were almost twice the levels measured at the two surrounding deserts (Table 2). In urban areas, emissions from agriculture and fossil-fuel combustion have significantly raised nitrogen inputs and hence the annual nitrogen deposition has doubled over the last century (Vitoussek et al. 1997; Fenn et al. 2003; Lohse et al. 2008; Hall et al. 2009). Several studies have demonstrated that AM fungal species can be affected for nitrogen deposition. For instance, Egerton-Warburton and Allen (2000) demonstrated that an anthropogenic nitrogen deposition gradient in southern California was associated with a shift in AM fungal community composition where larger spores from the genera *Gigaspora* and *Scutellospora* were replaced for a significant increase of smaller spores from the genera *Glomus* (*Glomus aggregatum* and *Glomus leptotichum*) as soil nitrogen levels increased. They also reported results with fertilized and unfertilized experimental plots that corroborated these shifts and concluded that the shift in AM community composition was mainly

produced by nitrogen deposition. In another study, Egerton-Walburton et al. (2001) used archived soils and air quality data from 1937 to 1999 to explore if changes in AM fungal species composition occurred over time with increased nitrogen emissions. They found that after 1975 AM diversity was reduced with the loss of three genera (*Acaulospora*, *Scutellospora* and *Gigaspora*), as well as species richness (lost of 1 species per year). A field experiment (with 8-year of nitrogen fertilization) by Johnson (1993) also demonstrated the decrease in abundance of certain species including *Gigaspora gigantea*, *Gigaspora margarita*, *Scutellospora calospora* and *P. occultum* while *G. intraradices* increased its abundance. She concluded that nitrogen fertilization may select less mutualistic and even detrimental AM fungal species. Further studies are necessary to determine if the absence of *Acaulospora* species in urban sites in Phoenix is associated with nitrogen deposition.

According to McDonnell and Hahs (2008) the use of specific measurements of urbanization can help scientists determine the response of organisms to urbanization. Even with the current study, which found significant differences between urban desert preserves and surrounding deserts, further research is required to assess the impact of urbanization on AM fungal communities. Futures studies may involve sampling a greater number of preserve study sites that may have varied in soil nitrogen deposition. Future studies could also use satellite imagery that detects impervious surfaces surrounding preserves and measurements of air pollution at study sites to detect the impact of these variables on AM and DSE fungi.

In conclusion, urban desert preserves and surrounding deserts in Phoenix, Arizona had some similarities such as analogous levels of DSE root colonization, the number of AM fungal species detected/sample, overall species composition and no evidence of exotic fungal species. There were some important differences that could indicate that urban desert preserves and

surrounding deserts were not functionally equivalent including lower AM root colonization percentage, lower total number of AM fungal species detected, lower species richness, and the absence of *Acaulospora* species at urban sites. Future studies in this area could include experimental greenhouse or field studies that could elucidate the direct impact of urban factors such as nitrogen deposition and disturbance of soils on AM fungal root colonization and AM species composition.

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APPENDIX A

PLANTS DETECTED AT STUDY SITES DURING THE SURVEY 200 IN 2000 AND 2005

Site	Life form	Common name	Scientific name
U131	Trees	foothills palo verde	*Parkinsonia microphylla*
	Shrubs/Herbs	desert lavender	*Hyptis emoryi*
		creosote bush	*Larrea tridentata*
		four o'clock	*Mirabilis bigelovii*
		narrow-leaved ditaxis	*Argythamnia lanceolata*
		slender janusia	*Janusia gracilis*
		buffelgrass	*Pennisetum cillare*
		bursage	*Ambrosia deltoidea*
		brittlebush	*Encelia farinosa*
		mormon tea	*Ephedra* sp.
		globemallow	*Sphaeralcea cf. ambigua*
		wolfberry	*Lycium* sp.
	Cacti/Succulent	barrel cactus	*Ferocactus cylindraceus*
		buckhorn cholla,	*Cylindropuntia acanthocarpa*
U201	Trees	foothills palo verde	*Parkinsonia microphylla*
	Shrubs/Herbs	ratney	*Krameria*
		buckwheat	*Eriogonum fasciculatum*
		bedstraw	*Galium stellatum*
		brittlebush	*Encelia farinosa*
		bursage	*Ambrosia deltoidea*
		goldeneye	*Viguiera parishii*
		rough jointfir	*Ephedra aspera*
		slender pore-leaf	*Porophyllum gracile*
	Cacti/Succulent	barrel cactus	*Ferocactus cylindraceus*
		boxing-glove cholla	*Cylindropuntia fulgida*
		hedgehog cactus	*Echinocereus engelmannii*
		ocotillo	*Fouquieria splendens*
		saguaro	*Carnegiea gigantea*
		teddybear cholla	*Cylindropuntia bigelovii*
AF141	Trees	foothills palo verde	*Parkinsonia microphylla*

	Shrubs/Herbs	mormon tea	*Ephedra.* sp.
		wolfberry	*Lycium* sp.
		buckwheat	*Eriogonum fasciculatum*
		bursage	*Ambrosia deltoidea*
		cat-claw acacia	*Acacia greggii*
		creosote bush	*Larrea tridentata*
		desert milkweed	*Asclepias subulata*
		four o'clock	*Mirabilis bigelovii*
		jojoba	*Simmondsia chinensis*
		white ratany	*Krameria grayi*
		wire-lettuce	*Stephanomeria pauciflora*
	Cacti/Succulent	buckhorn cholla,	*Cylindropuntia acanthocarpa*
		hedgehog cactus	*Echinocereus engelmannii*
		pencil cholla	*Cylindropuntia arbuscula*
		saguaro	*Carnegiea gigantea*
AD101	Trees	foothills palo verde	*Parkinsonia microphylla*
	Shrubs/Herbs	mormon tea	*Ephedra* sp.
		wolfberry	*Lycium* sp.
		buckwheat	*Eriogonum fasciculatum*
		brittlebush	*Encelia farinosa*
		bursage	*Ambrosia deltoidea*
		cat-claw acacia	*Acacia greggii*
		creosote bush	*Larrea tridentata*
		desert mistletoe	*Phoradendron californicum*
		fairy-duster	*Calliandra eriophylla*
		four o'clock	*Mirabilis bigelovii*
		jojoba	*Simmondsia chinensis*
		white ratany	*Krameria grayi*
		wire-lettuce	*Stephanomeria pauciflora*
	Cacti/Succulent	barrel cactus	*Ferocactus cylindraceus*
		buckhorn cholla	*Cylindropuntia acanthocarpa*
		christmas or pencil cholla	*Cylindropuntia leptocaulis*
		hedgehog cactus	*Echinocereus engelmannii*
		ocotillo	*Fouquieria splendens*
		pin-cushion cactus	*Mammillaria grahamii*
		teddybear cholla	*Cylindropuntia bigelovii*

Source: Grimm (2005)

APPENDIX B

PLANTS SAMPLED AT EACH STUDY SITE FOR MYCORRHIZAL ASSESSMENT, FEBRUARY 2008

Site	Sampling Point	Plant	Common name	Scientific name	AM root colonization %	DSE root colonization %	AM fungal species/sample
U131	1	Woody	brittlebush	*Encelia farinosa*	8	31	3
U131	1	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	20	41	5
U131	2	Woody	creosote bush	*Larrea tridentata*	35	1	4
U131	2	Succulent	nipple cactus	*Mammillaria* spp.	11	36	2
U131	3	Woody	bursage	*Ambrosia deltoidea*	21	29	3
U131	3	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	24	42	4
U131	4	Woody	bursage	*Ambrosia deltoidea*	35	15	4
U131	4	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	19	13	4
U131	5	Woody	bursage	*Ambrosia deltoidea*	18	33	4
U131	5	Succulent	barrel cactus	*Ferocactus cylindraceus*	9	31	3
U131	6	Woody	bursage	*Ambrosia deltoidea*	30	12	5
U131	6	Succulent	barrel cactus	*Ferocactus cylindraceus*	22	34	4
U131	7	Woody	bursage	*Ambrosia deltoidea*	30	31	5
U131	7	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	11	28	4
U131	8	Woody	creosote bush	*Larrea tridentata*	10	16	4
U131	8	Succulent	saguaro	*Carnegiea gigantea*	13	26	3
U131	9	Woody	bursage	*Ambrosia deltoidea*	36	24	5
U131	9	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	15	42	2
U131	10	Woody	foothills palo verde	*Parkinsonia microphylla*	39	35	4

U131	10	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	22	28	2
U201	1	Woody	bursage	*Ambrosia deltoidea*	3	6	5
U201	1	Succulent	hedgehog cactus	*Echinocereus engelmannii*	8	46	5
U201	2	Woody	bursage	*Ambrosia deltoidea*	2	28	5
U201	2	Succulent	ocotillo	*Fouquieria splendens*	11	32	5
U201	3	Woody	bursage	*Ambrosia deltoidea*	8	0	8
U201	3	Succulent	ocotillo	*Fouquieria splendens*	3	16	3
U201	4	Woody	bursage	*Ambrosia deltoidea*	5	6	3
U201	4	Succulent	hedgehog cactus	*Echinocereus engelmannii*	8	48	6
U201	5	Woody	bursage	*Ambrosia deltoidea*	7	10	7
U201	5	Succulent	saguaro	*Carnegiea gigantea*	6	48	5
U201	6	Woody	foothills palo verde	*Parkinsonia microphylla*	10	64	4
U201	6	Succulent	barrel cactus	*Ferocactus cylindraceus*	5	23	7
U201	7	Woody	bursage	*Ambrosia deltoidea*	17	37	5
U201	7	Succulent	saguaro	*Carnegiea gigantea*	21	26	6
U201	8	Woody	brittlebush	*Encelia farinosa*	3	21	6
U201	8	Succulent	saguaro	*Carnegiea gigantea*	6	13	7
U201	9	Woody	foothills palo verde	*Parkinsonia microphylla*	6	19	6
U201	9	Succulent	saguaro	*Carnegiea gigantea*	14	41	3
U201	10	Woody	foothills palo verde	*Parkinsonia microphylla*	2	31	3
U201	10	Succulent	saguaro	*Carnegiea gigantea*	6	39	2
AF141	1	Woody	creosote bush	*Larrea tridentata*	31	26	4

AF141	1	Succulent	hedgehog cactus	*Echinocereus engelmannii*	37	26	4
AF141	2	Woody	bursage	*Ambrosia deltoidea*	ND	ND	5
AF141	2	Succulent	saguaro	*Carnegiea gigantea*	22	21	3
AF141	3	Woody	bursage	*Ambrosia deltoidea*	20	16	4
AF141	3	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	10	18	5
AF141	4	Woody	bursage	*Ambrosia deltoidea*	30	20	4
AF141	4	Succulent	saguaro	*Carnegiea gigantea*	22	39	6
AF141	5	Woody	bursage	*Ambrosia deltoidea*	34	19	4
AF141	5	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	15	48	6
AF141	6	Woody	bursage	*Ambrosia deltoidea*	15	17	8
AF141	6	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	9	35	7
AF141	7	Woody	bursage	*Ambrosia deltoidea*	35	8	4
AF141	7	Succulent	christmas or pencil cholla	*Cylindropuntia leptocaulis*	25	28	5
AF141	8	Woody	bursage	*Ambrosia deltoidea*	11	19	2
AF141	8	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	15	26	4
AF141	9	Woody	creosote bush	*Larrea tridentata*	5	61	8
AF141	9	Succulent	hedgehog cactus	*Echinocereus engelmannii*	16	34	5
AF141	10	Woody	creosote bush	*Larrea tridentata*	17	10	6
AF141	10	Succulent	saguaro	*Carnegiea gigantea*	27	51	5
AD101	1	Woody	bursage	*Ambrosia deltoidea*	40	18	6
AD101	1	Succulent	barrel cactus	*Ferocactus cylindraceus*	25	33	5

AD101	2	Woody	foothills palo verde	*Parkinsonia microphylla*	65	16	4
AD101	2	Succulent	hedgehog cactus	*Echinocereus engelmannii*	41	12	3
AD101	3	Woody	jojoba	*Simmondsia chinensis*	77	4	4
AD101	3	Succulent	ocotillo	*Fouquieria splendens*	36	18	4
AD101	4	Woody	bursage	*Ambrosia deltoidea*	54	18	4
AD101	4	Succulent	buckhorn cholla	*Cylindropuntia acanthocarpa*	58	6	2
AD101	5	Woody	bursage	*Ambrosia deltoidea*	58	37	5
AD101	5	Succulent	ocotillo	*Fouquieria splendens*	36	23	5
AD101	6	Woody	creosote bush	*Larrea tridentata*	41	65	7
AD101	6	Succulent	christmas or pencil cholla	*Cylindropuntia leptocaulis*	46	11	4
AD101	7	Woody	bursage	*Ambrosia deltoidea*	46	19	7
AD101	7	Succulent	teddybear cholla	*Cylindropuntia bigelovii*	24	30	6
AD101	8	Woody	bursage	*Ambrosia deltoidea*	33	26	4
AD101	8	Succulent	teddybear cholla	*Cylindropuntia bigelovii*	17	29	3
AD101	9	Woody	bursage	*Ambrosia deltoidea*	54	11	7
AD101	9	Succulent	teddybear cholla	*Cylindropuntia bigelovii*	26	21	6
AD101	10	Woody	bursage	*Ambrosia deltoidea*	19	12	2
AD101	10	Succulent	teddybear cholla	*Cylindropuntia bigelovii*	22	34	3

ND=No data