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Nematode Community Response to Green Infrastructure Design in a Semiarid City

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Abstract

Urbanization affects ecosystem function and environmental quality through shifts in ecosystem fluxes that are brought on by features of the built environment. Green infrastructure (GI) has been suggested as a best management practice (BMP) to address urban hydrologic and ecological impacts of the built environment, but GI practice has only been studied from a limited set of climatic conditions and disciplinary approaches. Here, we evaluate GI features in a semiarid city from the perspective of soil ecology through the application of soil nematode community analysis. This study was conducted to investigate soil ecological interactions in small-scale GI as a means of assessing curb-cut rain garden basin design in a semiarid city. We looked at the choice of mulching approaches (organic vs. rock) and how this design choice affects the soil ecology of rain basins in Tucson, AZ. We sampled soils during the monsoon rain season and assessed the soil nematode community as a bioindicator of soil quality and biogeochemical processes. We found that the use of organic mulch in GI basins promotes enhanced soil organic matter contents and larger nematode populations. Nematode community indices point to enhanced food web structure in streetscape rain garden basins that are mulched with organic material. Results from this study suggest that soil management practices for GI can help promote ecological interactions and ecosystem services in urban ecosystems.

Core Ideas

- Ecological interactions are important for green infrastructure function.
- Green infrastructure soil management affected soil properties linked to function.
- Food web structure was more complex with soil management.
- Design and soil management enhanced ecosystem services of arid green infrastructure.

Urbanization is a landscape transformation with many impacts on water, air, and soil quality. A key feature of urbanization is a shift in the drivers of ecosystem fluxes through built environment impacts on climate, hydrology, and chemistry (Kaye et al., 2006). For example, impervious surfaces disconnect and isolate local ecosystem patches from inputs of water while at the same time impairing watershed functioning and quality (Paul and Meyer, 2001; Pickett et al., 2001). Such direct and indirect environmental impacts of urbanization can negatively affect the ability of local ecosystems to provide ecosystem services (Bolund and Hunhammar, 1999; Pataki et al., 2011; Pavao-Zuckerman, 2012). Green infrastructure (GI) is a best management practice (BMP) in urban landscapes that is expected to mitigate urban environmental impacts. For example, rain gardens are a multifunctional form of GI that can improve infiltration and soil water storage and remove nutrients from surface waters through bioretention processes (Hunt et al., 2012; Askarizadeh et al., 2015; Fletcher et al., 2015).

Green infrastructure can be designed to target specific functional goals. These goals often address stormwater management and water quality improvements, but they also align with broader environmental goals reflecting concepts of ecosystem services (Smith, 2009). Characteristics of GI that can be designed for specific functions include basin geometry, media or soil composition, the use of mulches, vegetation, surface area, and construction techniques (Hunt et al., 2012). Design approaches for GI soils often target infiltration rates (Hsieh and Davis, 2005) and bioretention processes (Liu et al., 2014). The use of mulches to surface-dress soils in GI serves as a barrier to evaporation of soil moisture, thereby supporting critical ecological functions (Watershed Management Group, 2012). Mulch has additional benefits in streetscape GI, including control of weeds, building soil organic matter (SOM), and reducing soil erosion. Different forms of mulch may be used to provide these benefits, depending on the setting and goals. For example, rock mulch may be desirable at sites with significant stormwater flows or where flooding is common, despite the lack of support for SOM, as organic mulches may be washed away. Identifying connections between GI design specifications and ecosystem service goals is an important part of ecological and environmental planning in cities.

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Abbreviations: BMP, best management practice; CI, Channel Index; EI, Enrichment Index; FB, fungivore-to-bacterivore ratio; GI, green infrastructure; SI, Structure Index; SOM, soil organic matter.

There has been little assessment of the actual performance of design aspects of GI elements in the context of cities (Pataki et al., 2011; Ahiablame et al., 2012). When GI has been evaluated, it is primarily from an engineering perspective, with ecological processes and dynamics receiving relatively less attention (Pataki et al., 2011; Ahiablame et al., 2012). Addressing these disciplinary gaps is particularly important for semiarid cities, where pulsed inputs of precipitation drive ecological function (Austin et al., 2004; Belnap et al., 2005; Collins et al., 2008) in ways that may alter the performance of GI as BMPs. The ability of GI to provide ecosystem services may be dependent on a suite of properties and processes related to soil management and quality as natural capital (Dominati et al., 2010).

Soil quality ultimately derives from the interaction of physical, chemical, and biological properties of soil (Karlen et al., 2003). Indicators of biological soil quality may be particularly informative of management effects (Lehman et al., 2015). This is because of the inherent sensitivity of biota to environmental changes (Bastida et al., 2008) and the critical role of soil organisms in regulating biogeochemical cycles (Wall et al., 2012). The soil food web drives the production and resilience of ecosystem services. The balance of soil microbial communities (e.g., bacteria vs. fungi) can affect decomposition, carbon (C) balance, and nutrient mineralization rates due to differences in life histories, environmental tolerances, and stoichiometric demands (Wardle et al., 2004). Soil invertebrates play critical roles in regulating ecosystem processes through direct regulation of microbial populations and physical effects on soil properties and decomposition substrates (Wolters, 2001; Mehring and Levin, 2015). Soil nematodes are used as an indicator of soil food web responses to environmental change and management because they have broad functional diversity, exhibit predictable responses to stress and disturbance, span a range of trophic levels, and bridge processes of detritivory, microbivery, and predation in soils (Bongers, 1990, 1999; Bongers and Ferris, 1999).

The soil nematode community is an important index of soil food web function and its contribution to soil quality (Bongers and Ferris, 1999; Neher, 2001; Wardle, 2002). Nematode community indices have been applied in urban settings (Pavao-Zuckerman and Coleman, 2007; Grewal et al., 2011) but have been used to a greater extent in assessing soil responses to agricultural management (Porazinska et al., 1999; Minoshima et al., 2007; van Eekeren et al., 2008; Zhang et al., 2012), forestry practices (Forge and Simard, 2001; Zhao et al., 2013), and restoration (Hohberg, 2003; Biederman et al., 2008). Studies using urban gradient approaches report that nematode species richness may be unaffected by urbanization (Pavao-Zuckerman and Coleman, 2007), but there is a turnover of species along urbanization gradients that reduces nematode functional diversity in response to local land management (Pavao-Zuckerman and Coleman, 2007; Li et al., 2011). Nematode community assemblages are responsive to soil water content and availability (Pavao-Zuckerman and Coleman, 2007; Amossé et al., 2016), atmospheric deposition, and heavy metal contamination (Ohtonen et al., 1992; Pouyat et al., 1994; Pen-Mouratov et al., 2010). Nematode community indices identify and reflect soil quality improvements for agricultural production in urban garden and vacant lot settings (Grewal et al., 2011). Nematode community analysis can also reflect changes in ecosystem function (Pavao-Zuckerman and Coleman, 2005; Knight et al., 2013). The functional and trophic ecology of nematodes is representative of different "energy channels" in the soil (e.g., bacterial vs. fungal) and has been linked to soil responses to plant management in urban restoration settings (Vauramo and Setala, 2010).

Despite their demonstrated success for indicating the impacts of urbanization and management on soils, nematode community analyses have not been used to assess GI. The soil nematode community should be indicative of the relative success of GI approaches, as GI is designed to affect soil physical and chemical properties. This study was conducted to investigate soil ecological interactions in small-scale GI as a means of assessing curb-cut rain garden basin design in a semiarid city. We asked if the soil nematode community is responsive and indicative to variation in GI design, specifically the choice of surface mulch applications. If the nematode community is responsive to design, we also wanted to assess whether there is a concurrent change in ecosystem processes and services. We hypothesized that the use of different mulching practices in GI design would shift the community of nematodes, particularly through the presence and absence of predatory and omnivorous nematodes.

Materials and Methods

This study was conducted in Tucson, AZ, in 2010. We studied streetscape GI installations that channel stormwater runoff from streets into residential soils via cuts in the curb. These curb-cuts feed water to rain garden basins that are depressions dug in the soil in the street-side right of way between the street and sidewalk (hereafter, these GI features are referred to as basins). The basins available in neighborhoods in Tucson for this study were designed according to best practices that were defined for ecosystems in the southwestern United States and that comply with City of Tucson regulations regarding right of way access, permitting processes, and maximum depths for standing water (Watershed Management Group, 2012). Design specifications for these basins include a width of 1.83 m, 6.1 m maximum length, a depth that is maintained at 0.203 m below the street surface, a maximum slope for basin sides of 33%, and a curb cut between 0.46 and 0.61 m (Watershed Management Group, 2012). Basin design for southwestern cities and environments balances pedestrian and vehicle safety, regulations for ponding water after storms, and principles to harvest stormwater to support plant growth, reduce flooding, and support bioretention processes (Lancaster, 2006; Watershed Management Group, 2012).

For this study, we selected basins that were installed in two neighborhoods in Tucson: Dunbar Spring and Rincon Heights. These two locations are ~2.4 km apart and are both ~1.5 km from downtown Tucson. They were selected for similarities in age and differences in soil management practices with respect to mulching. The Dunbar Spring site is classified as a mixture of "cave soils and urban land" with low infiltration rates and high runoff potential, and as "Sahuarita soils, mohave soils, and urban land" with medium runoff potential, whereas the Rincon Heights site is primarily classified as "cave soils and urban land" (Soil Survey Staff, 2017). Residents installed the basins in the Dunbar Spring neighborhood in 2007 to 2009, and their soils have been maintained with organic mulching practices (referred to below as organic mulch). These basins were initially surface mulched with noncomposted mesquite (primarily native velvet mesquite, *Prosopis velutina* Wooton) wood chips and bark pieces (B. Lancaster, personal communication, 2017). They were then maintained by residents by adding cut up stem prunings from the trees in the basins as the trees were trimmed, and the basins also received input of litter fall from the trees in the basins (B. Lancaster, personal communication, 2017). The basins in the Rincon Heights neighborhood were installed by residents (through the Rincon Heights Neighborhood Association) and a local nonprofit (Watershed Management Group) in 2009 and were installed with surface rock mulch (referred to below as rock mulch). Best practices for rock mulch include using 0.1- to 0.2-m "rip rap" rock at the basin inlet and bottom and 0.025 m gravel on the basin slopes (Watershed Management Group, 2012). These basins also received input of litter fall from the trees in the basins, but no stem clippings were added over time. The choice of organic versus rock mulch represents a critical design feature where both choices can serve as barriers to evaporation of soil moisture. In the Dunbar Spring neighborhood, residents adopted permaculture practices, so organic mulch was selected to promote SOM and C accumulation (Lancaster, 2006). Rock mulch was selected in the Rincon Heights neighborhood to minimize the maintenance involved in replacing any lighter organic material that might be washed away after intense rain events (Watershed Management Group, 2012). Despite the standardized design specifications discussed above (Watershed Management Group, 2012), the basins in the two neighborhoods differed in their flow accumulation areas, with the basins in Dunbar Spring accumulating flow from smaller areas than those in Rincon Heights (30.7–371.6 m^2 and 603.9–11,091.5 m^2, respectively, as determined from a 0.61-m resolution digital elevation model; E, Canfield, personal communication, 2017).

We selected basins for this study from these neighborhoods that were all planted with native mesquite trees (*P. velutina).* We chose five organic mulch and five rock mulch basins to sample for soil properties and nematode analyses. We sampled soils from the basins ~2 wk into the 2010 summer monsoon season. We collected all soil samples 2 d after 31.5 mm of precipitation was recorded (over 4 d) at a weather station located between 10.8 and 13.7 km from the two neighborhoods (National Centers for Environmental Information, 2017). We collected soil samples by clearing away any loose litter and duff layer and extracted soil samples using a 5 cm diameter and 10 cm deep corer. We collected four cores from each basin and then bulked these together to account for spatial heterogeneity of soil properties. An additional core was collected intact for bulk density analysis. Soils were transported in coolers on ice and stored at 4°C until analysis.

Soils were sieved (4 mm), and a subsample of the sieved soil was air dried for chemical and physical analysis. Soil moisture contents were determined calculating the water lost by drying a subsample of soil for 3 d at 105°C. SOM content was determined by loss on ignition (ashing at 450°C for 6 h in a muffle furnace). The loss on ignition method will overestimate SOM contents due to the loss of carbonates in the ashing processes. Microbial biomass was assayed using a chloroform fumigation and extraction procedure that provides an estimate of the size of microbial populations using their C content (Vance et al., 1987). Soil nematodes were extracted (alive) from 10-g subsamples of unsieved field-moist soil using Baermann funnels, fixed and preserved with 5% formalin. All nematodes in each sample were counted and identified to family with an inverted microscope. Nematode families were then counted by trophic group according to Yeates et al. (1993a): bacteriovores, fungivores, carnivore, omnivores, and plant feeders.

We used family-level counts to calculate weighted faunal indices that allow for assessment of the soil food web through analysis of community composition data (Ferris et al., 2001). The Enrichment Index (EI) and Structure Index (SI) are expansions of a functional guild index, where all taxa in a functional guild have the same feeding habit (Yeates et al. 1993a) and the same value on a colonizer to persister scale (maturity index; Bongers, 1990). The EI and SI are calculated using a weighting system of these nematode functional guilds across hypothesized trajectories of response to contribution to food web structure and resource enrichment (Ferris et al., 2001; Pavao-Zuckerman and Coleman, 2007). The fungivore-to-bacterivore ratio (FB) and the nematode Channel Index (CI) were also calculated as indicators of decomposition pathways in the soil. The FB ratio was calculated as [fungivores/(fungivores + bacteriovores)] (Yeates et al., 1993b), and smaller values were indicative of faster rates of decomposition and nutrient cycling (Söhlenius and Sandor, 1988). The CI is a weighted ratio of fungivores to bacterivores (Ferris et al., 2001). Soils with a greater CI score are indicative of fungal dominance in decomposition pathways and energy channels (Ferris et al., 2001).

We also were interested in assessing how the basins affected the functional attributes of the nematode community and how these attributes affected ecosystem services. To assess functional attributes, the metabolic footprints of the nematode community were assessed according to Ferris (2010), in addition to the structural indices described above. The metabolic footprint approach uses existing data on nematode biovolumes, growth rates, and the weightings used in EI, SI, and CI calculations (Ferris et al., 2001) to estimate the C metabolism of the nematode community (Ferris, 2010). Enrichment Index, SI, CI, and metabolic footprints were calculated using the online Nematode INdicator Joint Analysis (NINJA) tool (Sieriebriennikov et al., 2014, 2017).

To assay soil microbial function in the different soils, we used short-term nitrogen (N) turnover that indicates both microbial function and bioretention properties. Potential N-mineralization and nitrification rates were determined by incubating 25-g subsamples of soil at field moisture content for 14 d at 25°C. Soils were extracted with 2 M KCl and the filtrate was analyzed for NH_4–N and NO_3–N content (with an Acquity ultra-performance liquid chromatograph).

All data were log transformed prior to statistical analysis to address assumptions of normality as assessed through Kolmogrov–Smirnov tests. Differences between mean data were analyzed with *t* tests using the JMP statistical software (SAS Institute, 2010). Correlation analyses between abiotic and biotic drivers, including soil moisture, SOM, microbial biomass, and nematode community and N-mineralization data, were conducted.

Results and Discussion

Gravimetric soil moisture contents were twice as great in the basin soils that were mulched with organic material than those mulched with rocks, despite having smaller areas of impervious surfaces draining into the basins (Table 1, $p < 0.05$). Soil organic matter content was also twice as high in the soils that were mulched with organic material than those mulched with rocks (Table 1, $p < 0.05$). While the loss on ignition method can overestimate SOM in arid soils, the SOM contents in the organically mulched basins are within the ranges reported under mesquites in natural grasslands in southern Arizona (Cable et al., 2009) and in urban soils in other Sonoran desert cities (Hall et al., 2009). Microbial biomass C content did not differ significantly between mulch types (Table 1). An increase in the soil microbial biomass pool would be consistent with microbial responses to restoration in other settings where organic amendments are added or allowed to return to soils (Baer et al., 2002). Although the use of GI in cities is not a formal restoration practice, concepts and approaches from ecological restoration are appropriate to frame the analysis of GI in the context of designed urban ecosystems (Higgs, 2016). The response of microbial populations can sometimes be relatively rapid with restoration interventions, providing some hope for a quick return of ecological structure and function in cities with the implementation of GI (Harris, 2009; Jones and Schmitz, 2009). Composting of organic residues may contribute to successfully promoting soil C and microbial pools (Ros et al., 2003), which may explain why microbial biomass was nonresponsive to soil changes influenced by the use of organic mulch in this study. The incorporation of composting as a management and design principle in semiarid GI installations is a BMP that should be explored further.

The soil nematode community was significantly affected by the different mulch approaches in this study (Table 2). Total nematode abundance was 10 times greater in basins with organic mulch than when rock mulch was used as a ground cover (Table 2, $p < 0.001$). The use of organic mulch also increased the number of families. In basins with rock mulch, the families identified included Rhabditidae, Aphelenchidae, Cephalobidae, and Dorylaimidae. Although Rhabditidae were not observed in the basins with organic mulch, additional families included Monhysteridae, Mononchidae, and Aporcelaimidae. An increase in nematode abundance in the organic mulch basins implies that their food resources were elevated at some point in time, yet we did not observe differences in microbial biomass C contents (Table 1). The responses of soil microbes to precipitation inputs in arid ecosystems are short lived (McCrackin et al., 2008), and soil fauna and microorganisms exhibit different ranges of optimal soil moisture contents (Whitford, 1989). By sampling at a single point in time, we may have missed the dynamics of interacting populations growing and decaying in response to the pulse of water as it changed moisture contents after the precipitation event.

Differences in nematode abundance and taxonomy translated into differences in community structure, as indicated by functional feeding group relative abundances (Table 2). For example, there was a significant increase (four times greater) in the relative abundance of fungal-feeding nematodes in basins with organic mulch than with rock mulch. This increase in abundance led to an increase in the fungal-feeding to bacterial-feeding nematode ratio with the use of organic mulch and a greater CI value in these soils as well (Table 2). Whereas the soils still reflect the presence of bacterially dominated energy pathways (Wardle et al., 2004), the elevated presence of fungal-feeding nematodes suggests that there is an enhanced fungal abundance in the basins with the organic mulch compared with those with the rock mulch. The

Table 1. Mean soil characteristics from curb-cut rain garden basins with different mulching approaches in Tucson, AZ (mean data ± 1 SE are presented in parenthesis).

Basin type	Bulk density	Gravimetric water content	Soil organic matter	Microbial biomass carbon
	g cm^{-3}	g H_2O g soil^{-1}	%	μg C g dry soil^{-1}
Rock mulch	1.72 (0.18)	0.08 (0.01)*	5.3 (1.3)*	0.20 (0.11)
Organic mulch	1.70 (0.09)	0.22 (0.04)	10.8 (1.2)	0.29 (0.05)

* Significant at the 0.05 probability level.

Table 2. Mean total nematodes, mean nematode functional feeding group relative abundances, and mean index values from curb-cut rain garden basin soils with different mulching approaches in Tucson, AZ (mean data ± 1 SE are presented in parenthesis). Nematode weighted faunal analysis profiles (see text and Ferris et al., 2001) for soils characterize the response and trajectory of soil food webs to restoration, disturbance, and stress.

	Basin type	
	Rock mulch	Organic mulch
Total abundance (g dry soil^{-1})	0.8 (0.2)***	8.5 (0.9)
Bacterivore relative abundance (%)	84.4 (4.7)**	64.6 (3.9)
Fungivore relative abundance (%)	3.1 (1.6)*	14.8 (5.4)
Omnivore relative abundance (%)	12.5 (3.6)	3.5 (3.5)
Carnivore relative abundance (%)	0.0*	17.0 (7.5)
Fungivore-to-bacterivore ratio	0.04 (0.06)	0.21 (0.7)
Enrichment Index	27.9 (2.1)	14.2 (5.2)
Structure Index	32.1 (18.5)	51.5 (10.4)
Channel Index	25.0 (25)	100 (0)
Composite metabolic footprint	0.37 (0.06)	7.95 (3.9)
Enrichment metabolic footprint	0.08 (0.07)	0.16 (0.07)
Structure metabolic footprint	0.17 (0.09)	6.74 (3.8)

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

abundance of fungal-feeding nematodes and the CI values were likely influenced by the nature of the organic mulch chosen by the homeowners, in this case, woody plant material (mesquite wood chips and branches). Monitoring of these GI features over time may capture shifts in relative contributions of bacteria and fungi to the energy pathways in the soil food web.

The abundance of predatory (omnivorous and carnivorous) nematodes were six times greater when organic mulch is used, and no carnivorous nematodes were found in the rock-mulched basins (Table 2). The increase in bacterial-feeding and fungal-feeding nematode abundances in the organically mulched basins indicates more food for predatory nematodes in these basins. The structure footprint was elevated in the organically mulched basins and can be considered as an indication of enhanced metabolic activity of higher-trophic-level nematodes (Ferris et al., 2012; Zhang et al., 2015). These differences in abundances in feeding groups also affected indices of soil food web function and structure. The presence of GI regardless of mulching brings more structure to soil food webs, whereas the use of organic mulch reduces the EI. The organic mulch was primarily mesquite wood chips and branch clippings, and its relative composition with respect to C and lignin (Ritter and Fleck, 1922; Scharenbroch et al., 2013) likely favored fungal populations (Shah and Nerud, 2002; de Boer et al., 2005) and thereby influenced the abundance of fungal-feeding nematodes and FB and CI values. The nematode indices can also be interpreted in comparison with other studies of nematode community indices in other settings (Ferris et al., 2001). The index scores of the rock-mulched basin soils are comparable with sites that are described as "maturing." These maturing sites may have low to moderate disturbance and tend to be nutrient enriched. The scores for the organic mulched soils are comparable with sites that may be "structured," which tend to have lower levels of disturbance and nutrient enrichment and higher abundances of fungal feeders.

The nematode community analyses can be extended to characterize functional attributes by calculating the metabolic footprints of different functional groups and the faunal indices described above (Ferris, 2010; Ferris et al., 2012). The enrichment footprint for both basins was relatively low, indicating inputs of relatively low-quality organic matter into the soil food web. The structure footprint was elevated by the use of organic mulches and is an indication of the metabolic activity of higher-trophic-level nematodes (Ferris et al., 2012; Zhang et al., 2015). The elevated structure footprint, along with the elevated abundance of predatory and omnivorous nematodes, is indicative of an enhanced regulatory ecosystem service of the soil food web in the organically mulched basins (Ferris, 2010; Ferris et al., 2012).

We found that the soil nematode community was responsive to mulching treatments, including an increase in fungal feeders in the soil food web with the use of organic mulch. Our results contrast with other studies that report a suppression of fungal-feeding nematodes when using a variety of organic compost amendments (Renco et al., 2010), likely because the amendment in this study was not composted and composed largely of wood chips and branch clippings. The relative balance of fungal versus bacterial energy pathways in the soil food web is an important property linking ecological structure and function and the provision of ecosystem services, because these groups of organisms respond differently to environmental conditions and stress and play different roles in driving decomposition and nutrient cycling processes (Hunt et al., 1987; Wardle et al., 2004). For example, fungal-dominated soil food webs are indicative of lower N losses through leaching, an important regulatory ecosystem service of GI (de Vries et al., 2011). Fungal-dominated food webs, and thus the C and N processes they drive, may be more resistant to drought (de Vries et al., 2012), an important consideration for the resilience of GI to dry-wetting dynamics in semiarid environments (Huxman et al., 2004a; Collins et al., 2008; Knerl, 2014), a supporting ecosystem service. Fungal dominance is an important indicator of restoration success, and strategies to speed the pace of recovery include approaches that shortcut natural successional trajectories to bring fungal dominance early to a restored site (Harris, 2009). Although the soils in this study exhibited bacterially dominated energy pathways, the increase in fungal-feeding nematodes is suggestive of a trajectory of development that includes a stronger role for fungal pathways in the soils of GI features. The nematode faunal analyses also point to the role of predatory nematodes in providing additional ecosystem services in the organically mulched basins. The elevated structure footprint, along with the elevated abundance of predatory and omnivorous nematodes, is indicative of an enhanced ecosystem service of the soil food web in the organically mulched basins, as nematodes may regulate the dynamics of microbial populations (Ferris, 2010; Ferris et al., 2012). Future studies may confirm further development of these communities and their role in the functioning and ecosystem services of these urban soils.

Studies that use soil fauna as bioindicators suggest that it is important to distinguish the difference between direct trophic and indirect environmental impacts of organic amendments on soil nematodes in the context of environmental restoration (Biederman et al., 2008). In this study, the nematode community was correlated more strongly with soil moisture ($R^2 = 0.43$, $p < 0.04$) than with the soil microbial biomass ($R^2 = 0.13$, $p = 0.31$) or SOM content ($R^2 = 0.22$, $p < 0.16$), suggesting that mulch has its greatest impacts through indirect effects on soil moisture, an important property of soils in semiarid ecosystems. However, the relationships between microbes and nematodes as dynamic soil food web responses of these GI features are likely complicated by time lags that result from different life courses, life spans, and optimal soil moisture contents for different species of soil microbes and microfauna (Whitford et al., 1981; Whitford, 1989; Paul, 2007; Sponseller, 2007). Still, the role of organic mulch in GI may still be important for the dynamics of soil food webs. Studies of grassland restoration have indicated that organic amendments may stimulate plant growth and root exudation, resulting in a food web dominated by organisms that are adapted to responding rapidly to resource inputs (Biederman et al., 2008).

The findings from this study should be interpreted with some reservation, as soil samples represent a single point in time. Rain garden basins are dynamic in time in several ways. For this semiarid system, there is a pulse-response nature to ecological dynamics in response to rainfall inputs that likely drive both surface and stormwater flows, as well as the dynamics of the soil nematode community (Huxman et al., 2004b; Reynolds et al., 2004). These dynamic responses occur over the span of minutes to hours to days as soils wet and dry down again (Schwinning and Sala, 2004; Saetre and Stark, 2005). It is likely that food web dynamics also are responsive to precipitation pulses, but this has not been well explored in semiarid soil

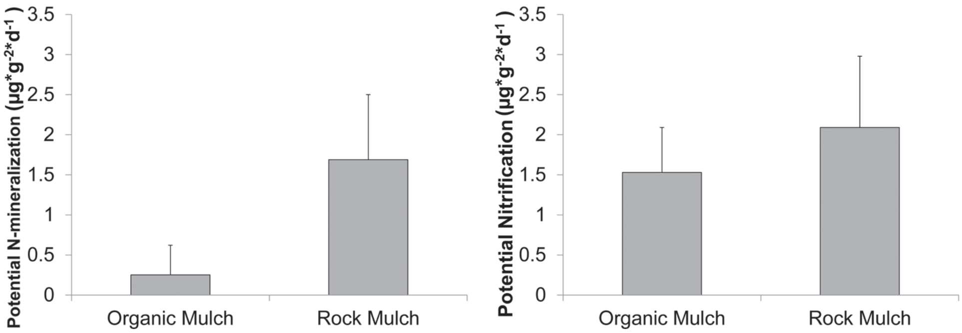

Fig. 1. Mean potential nitrogen mineralization and potential nitrification rates averaged for soils from curb-cut rain garden basins with different mulching approaches in Tucson, AZ (mean data ± 1 SE). Soils were incubated for 14 d at 25°C and field moisture conditions.

ecosystems (Whitford, 1989). Because the pulse-response dynamic is so critical for ecological function in semiarid ecosystems, subsequent studies should focus on the temporal dynamics of wetting and drying and their implications for rain garden function.

Mulching approach did not significantly affect potential N-mineralization rates (Fig. 1), likely due to small sample size. In some settings, C availability influences the dynamics of soil organisms and supports enhanced biotic N assimilation (Ehrenfeld et al., 2005). With greater abundances of nematodes and elevated SOM in the organically mulched basins in this study, we also observed a connection between C resource availability, soil organisms, and food webs, a supporting ecosystem service of the mulching approach (although we did not observe a difference in microbial biomass between basins). Although the N-mineralization data did not indicate significant differences, the enhanced soil faunal populations in the organically mulched basins may drive similar processes in comparison with the rock-mulched basins that further expanded studies should focus on. The CI and FB ratios (Table 2) are indicative of further regulating ecosystem services, including slower rates of nutrient turnover in the organic mulched basins (Ferris et al., 2001; Neher et al., 2005). Additionally, the increase in fungal feeders in the organically mulched basins may indicate the role of the soil food web in enhanced N immobilization in soils (Schimel and Bennett, 2004). Although nonsignificant, the production of potentially mineralizable N in the rock-mulched basins suggests that the choice of GI design features may affect N dynamics at the interface of urban soil and stormwater. Further studies that bridge ecological, biogeochemical, and hydrologic data are needed to explore the mechanisms by which GI contributes to watershed dynamics in arid ecosystems. While both rock and organic mulch may be used in GI designs for their ability to reduce evaporative losses (Watershed Management Group, 2012), our results indicate that the selection of organic mulch may provide additional ecosystem services linked to population regulation and trophic dynamics of the soil food web. The differences in soil quality with respect to SOM, soil food web complexity, and ecosystem services in this study suggest that soil ecological interactions can inform the design of GI BMPs in urbanized watersheds.

Conclusions

This study was conducted to investigate the role of ecological interactions in small-scale GI as a means of assessing curb-cut rain garden basins in a semiarid city. We investigated how design choices with respect to soil surface mulching affects the soil ecology of semiarid GI installations. We describe soil food web composition, along with soil nutrient cycling processes in GI with different soil management strategies. This study demonstrates that increasing structure of the soil food web accompanies the use of organic mulches in streetscape GI and that the soil nematode community may be indicative of ecological interactions resulting from reconnecting ecohydrologic and detrital pathways in urban ecosystems. Although direct linkages between the community of soil organisms of GI and watershed-scale processes have yet to be demonstrated, the role that soil community structure and species interactions play in driving local processes and soil ecosystem services may scale up to landscapes and watersheds (Doran and Zeiss, 2000). Thus, the results of this study suggest that soil management practices, such as the use of organic mulches in GI rain garden basins, can help promote soil ecological interactions and ecosystem services in GI in semiarid urban ecosystems.

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