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Scratching the surface and digging deeper: exploring ecological theories in urban soils

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Introduction

Humans have altered the Earth more extensively during the past 50 years than at any other time in history (Millennium Assessment 2003). A significant part of this global change is the conversion of land covers from native ecosystems to those dominated by human activities (Kareiva et al. 2007; Ellis and Ramankutty 2008). Although agricultural needs have historically been the dominant driver of land cover change (Millennium Assessment 2003), urbanization is now emerging as a primary process of land cover transformations around the world. As a result, urban ecology has emerged as an important research focus because of the increasing spatial extent of, and human population sizes in, urbanized ecosystems (Grimm et al. 2008a).

Similarly to urbanized ecosystems, over the past several decades soils have been receiving increasing research attention due, in part, to growing appreciation of their linkages with aboveground ecosystems (Wardle et al. 2004; Wall et al. 2005) and global biogeochemical cycles (Schlesinger and Andrews 2000), and their roles in providing and regulating essential ecosystem services (Wall 2004). Yaalon (2007) recently pointed out that, although often underappreciated, soils are greatly impacted by human-mediated land cover changes and that greater understanding and mitigation of the impacts is needed to ensure the future sustainability of societies. Anthropogenic impacts on soils are perhaps most dramatic in urbanized ecosystems where humans remove, reconfigure, and pollute them to a greater degree than in other contexts (DeKimpe and Morel 2000). In this special issue of Urban Ecosystems, the two topics of urbanized ecosystems and soils are integrated

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within a series of papers focused on the basic and applied aspects of research in urban soil ecology.

These papers arose from a symposium we organized for the 2004 annual meeting of the Ecological Society of America. In a general sense, the question guiding the symposium was: What can we learn about the generality of ecological systems and theories by studying urban soils? As such, the focus of the symposium was to review and discuss current understanding of urban soils with a particular focus on how studying them can contribute to the development and testing of ecological theory. We invited a diverse group of speakers to create a panel that addressed multiple ecological perspectives, including biodiversity, biogeochemistry, invasive species, landscape ecology, restoration ecology, and environmental education. Speakers were asked to think of "urban" in a broad sense, so rather than constraining discussion to cities proper, they also included analyses that draw on insights from suburban and exurban environments (collectively, urbanized ecosystems). In addition, we asked symposium presenters to consider: (1) what characteristics of urban ecosystems and urban soils are similar to and different from other ecosystems, and (2) how modifications of heterogeneity in abiotic conditions, resource availability and disturbance regimes provide a theoretical context with which to examine the ecology of soils in urbanized environments. These two themes are carried through the collection of papers in this special issue.

In this introductory paper, we set the stage for the other papers by discussing how the study of urban soil ecology has relevance to both general ecological theory and development of applied knowledge for sustainably managing urbanized ecosystems. To facilitate this discussion, we present a conceptual model to frame and organize the examination of how urbanization modifies soils and their ecology; this model is built around dimensions of general ecological theory that we posit have central relevance to understanding drivers of ecological patterns and processes in urban soils. We then provide an overview of the papers in this special issue, discussing them within context of the conceptual model and highlighting their relevance to applying ecological knowledge to managing urban soils. Finally, we discuss frontiers for the study of urban soil ecology to help spark future studies that will "dig deeper" into this nascent but critically important topic.

A conceptual model for urban soil ecology

Arguably, the theories underpinning ecological science are biased in two ways due to (largely) historical legacies. First, their development has been dominated by aboveground perspectives and studies, certainly in large part because of the challenges of studying the soil habitat and its organisms (Coleman and Crossley 1996; Wall et al. 2005). Nonetheless, as many have argued, soils should play a more prominent role in testing and developing ecological theories because of their high levels of taxonomic and functional biodiversity, their importance as sites of many ecological processes, and their relationships with aboveground ecosystems (Wardle and Giller 1996; Ohtonen et al. 1997; Young and Ritz 1998; Wall et al. 2005).

A second trend in the development of ecological theories is that they have largely been derived from the study of environments lacking a significant human presence, including, and especially, urbanized ones. However, as is true for soils, inclusion of urbanized ecosystems into further testing and development of ecological theory may yield new insights about ecological dynamics (Pickett et al. 2008), especially as they are influenced by, and influence, humans and sociocultural variables, an important contemporary dimension in ecological science (Palmer et al. 2004; Redman et al. 2004). In particular, ecological theories relevant to the study of soil and urbanized ecosystems include (but are not limited to) those describing relationships between (1) biodiversity and ecosystem function, (2) disturbance and resilience, (3) resources and food web structure, and (4) causes and consequences of spatiotemporal heterogeneity of biota and abiota. To various degrees, investigations of these theoretical dimensions have been completed by both soil and urban ecologists. However, we suggest that integrating these two sub-fields presents even greater opportunities to explore ecological theories through the study of urban soil ecology.

One helpful way to integrate sub-fields is to examine relationships among the concepts underpinning them through creation of a conceptual model (or framework) (Allen and Hoekstra 1992; Pickett 1999; Pickett et al. 2007). Conceptual models are necessary tools for organizing the components of complex systems into a framework that facilitates the development of questions and theories (Groffman et al. 2004a). Thus, we developed a novel conceptual model to help frame the discussion of urban soil ecology (Fig. 1) by focusing on environmental variables that we posit are central drivers of ecological patterns and processes in urban soils.

The framework begins with the context of urbanization as a broader process that impacts soils. Although soils are rarely if ever a direct target of the goals of processes that drive urbanization, they are indirectly impacted by urbanization processes as humans remove, replace or otherwise modify soils as means to other ends (e.g., construction of roads, buildings, and lawns; (DeKimpe and Morel 2000)). The ends that humans have for urbanized ecosystems are diverse. As such, a central emerging theme of urban ecology is that urbanized ecosystems are characterized by high levels of spatial heterogeneity and patchiness (Grimm et al. 2008a; Grimm et al. 2008b; Cadenasso and Pickett 2008). Although in most cases urbanization and urban landscape management are targeted toward

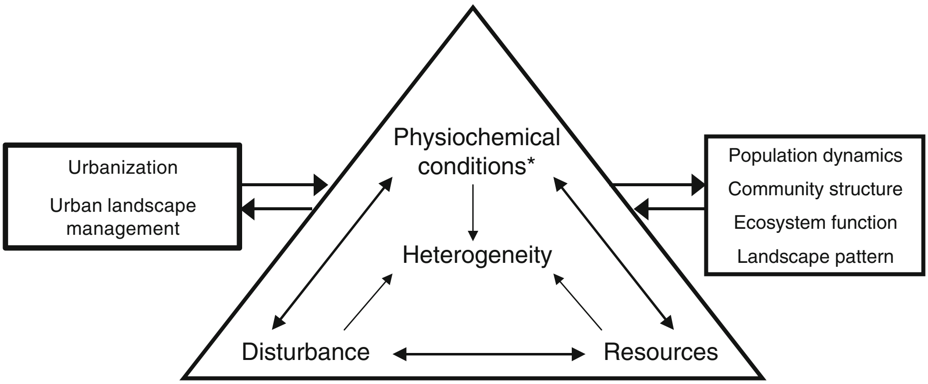

Fig. 1 Conceptual model of how urbanization and subsequent urban landscape management generates ecological effects on soils. The processes of urbanization and landscape management by humans (at left) change the ecological parameters (at right) at a variety of scales by creating heterogeneity in physicochemical conditions, disturbance regimes, and resource availability; these variables interact with and affect each other in various ways. In the right box, variables across the levels of ecological organization have numerous direct and indirect relationships with each other (not illustrated for simplicity), many of which may be mediated by variables in the triangle. In turn, ecological variables associated with the box at right can have effects on the variables within the triangle, leading to feedback loops. The degree to which such feedback loops can then affect urbanization patterns and human decisions about urban landscape management are not clear but should be explored in further studies that integrate sociocultural and ecological variables

aboveground structure and function, all processes and activities associated with urbanization can be expected to have some effect on the belowground ecosystem (Byrne et al. 2008). In turn, urban soils and their ecological patterns can also be expected to have high spatial heterogeneity, an important driver and mediator of soil communities and soil processes in all ecosystems (Ettema and Wardle 2002; Pickett et al. 2008). Thus, a key theme for urban soil ecology research should be examination of the spatial heterogeneity of soil ecological patterns and processes and linkage of them with patterns of aboveground landscapes and human activities (DeKimpe and Morel 2000).

As part of a general urban soil ecology framework, we suggest that a focus on three variables will facilitate the mechanistic understanding of spatial heterogeneity of ecological patterns and processes in urbanized soils: (1) resource availability (e.g. detritus, water, inorganic N), (2) abiotic (or physicochemical) conditions (e.g., temperature, pH, metals), and (3) disturbance regimes (e.g., mowing, pesticides, compaction). In our framework, these three factors affecting heterogeneity across space are also temporally dynamic; as such, the triangle can be interpreted as the Greek letter delta which symbolizes the importance of "changes in" these factors as drivers of ecological dynamics in urban soils. In turn, interactive feedbacks among these three dimensions across a range of small to large spatiotemporal scales are expected to affect a range of both above- and belowground ecological variables (right box in Fig. 1). Feedback loops may emerge where changes in the structure and dynamics of populations, communities, ecosystems and landscapes will generate another layer of heterogeneity of urbanized soils along with that directly created by humans through their alteration of abiotic conditions, resource availability and disturbance regimes (i.e., an arrow points from the right box to the triangle in Fig. 1; (Pouyat et al. 2006)). If and how appreciation of such feedback loops can then inform human decisions and activities to effect positive changes in urbanization rates and patterns to increase the sustainability of urbanized environments (i.e., arrow from triangle to left box in Fig. 1) remains a question in need of further interdisciplinary investigations (Palmer et al. 2004).

Papers in this volume

In the opening article of this issue, Pickett and Cadenasso further discuss the components of the central triangle of the urban soil ecology framework (Fig. 1) with an overview of concepts that are useful for understanding how urban soils can be used to investigate ecological theories. In particular, they provide a comprehensive review of how resources, physicochemical conditions and disturbance interact to generate spatiotemporal heterogeneity in urban soils and, thus, their ecological patterns. Their discussion is organized around Jenny's (1941) state formation model, which is used to help illustrate the factors that help shape soils within an urban environment. The actions of humans affect the soil formation factors of climate, topography, organisms, time and parent material through disturbance, altered resources, and heterogeneity. These effects can be direct influences, but there are also many indirect feedbacks. In particular, human control of plant communities and other land covers can affect urban soil patterns through modification of organic inputs and abiotic conditions (Hope et al. 2003; Byrne et al. 2008). In addition, Pickett and Cadenasso argue that—as for urban ecology in general—sociocultural factors that affect landscape design and management practices (e.g., aesthetic values, financial resources) must be incorporated into urban soil ecology research for a more holistic understanding of how urban soils are formed (Grimm et al. 2008a; Byrne and Grewal 2008).

The issue's other four articles provide specific perspectives for different approaches to understanding soils in an urban context. The first three provide insights from the perspectives of biogeochemistry, landscape ecology, and restoration ecology, while the fourth brings appreciation of urban soils into the realm of environmental education. In their paper, Pouyat, Yesilonis, and Golubiewski discuss the role of urban soil management on soil carbon storage. Their research compares patterns of soil organic carbon stocks in Baltimore, Maryland and Denver, Colorado, allowing them to determine the interactive effects of climate, native vegetation type, and urban land use on soil carbon stocks. The paper provides insights into how urban land use affects biogeochemical cycling through effects on the physico-chemical environment of soil, disturbance regimes, and resource availability (Fig. 1). Their study expands recent analyses about how soil C stocks within urban land use types contribute to our understanding of regional and global C pools and fluxes, a critical need for responding to issues of increases of atmospheric carbon dioxide and global climate change (Pataki et al. 2006).

Byrne (2007) links human activities and soil ecology through a literature review discussion of how human management of aboveground habitat structure in urbanized landscapes affects a range of variables that then impact soil properties. He argues that the study of urban soil ecology requires the use of a fine, patch- and point-scale perspective because basic soil research is conducted "on the ground" at specific locations and because individual bounded patches (or parcels) are the spatial scale at which humans manage urban landscapes (Byrne and Grewal 2008). The concept of habitat structure provides an operational approach for comparing the mechanistic relationships among the spatiotemporal heterogeneity of sociocultural variables and ecological variables across specific patches and points. In addition, habitat structure provides a useful perspective for understanding how human-mediated disturbance in urbanized ecosystems affects belowground variables; for example, lawn mowing is a method for managing aboveground habitat structure but this disturbance also affects soil properties through inputs of dead organic matter to the soil (Shi et al. 2006; Byrne et al. 2008). Moreover, habitat structure helps bridge ecological theory and landscape management because people are more familiar with thinking about management of structures more than abstract ecological concepts of resources, abiota, and disturbance. Thus, the habitat structure framework in Byrne's article may be a useful starting point for educational programs that help people understand how their landscaping activities affect soil properties.

Heneghan, Umek, Grandy, Jabon, and Bernau discuss the necessity of considering soils for improving the practice of restoration ecology and conservation of biodiversity in urban settings. The practice of restoration ecology has been called the acid test of our ecological understanding (Bradshaw 1987). Nowhere is this more apparent than in cities, where often the very soil substrate needs restored because of extreme alteration or removal (e.g. see Pickett and Cadenasso) and humans play a more direct role in governing the developmental and evolutionary trajectories of ecosystems (Kareiva et al. 2007). The implications for restoration ecology in cities is that we must reconsider concepts of baselines, goals, and targets, as well as the processes of evaluation and assessment and even the practice of restoration itself (Ehrenfeld 2000; Pavao-Zuckerman 2008). Furthermore, Heneghan et al.'s paper hints at the utility of insights gained from studying urban soils for understanding alternative stable states and the management of urban systems for greater ecological resilience in response to both social and environmental disturbances.

Finally, Johnson and Catley demonstrate the relevance of urban soils for environmental education. Soils in urbanized environments are excellent learning laboratories that provide students with opportunities to get their hands dirty (literally) and directly experience nature in an urban environment. Johnson and Catley suggest that capitalizing on linkages between the local soils that people experience and ecosystems at global scales lays a foundation for effective environmental and sustainability education. The long-term impact of such educational and tactile experiences is just beginning to be explored, but it is reasonable to expect that urban environmental education with an emphasis on experimental learning provides some counter to the "extinction of experience" and "nature-deficit disorder" that are thought to accompany the process of urbanization (Turner et al. 2004; Miller 2005; Louv 2008).

Digging deeper into urban soils

The papers in this special feature provide examples of how ecological theory is being explored in studies of urban soils. The ecological and environmental changes brought about by processes of urbanization can be conceived of as experimental "treatments" on soil plots (McDonnell and Pickett 1990) to investigate ecological patterns and processes. Often these manipulations may be of the scale that we might want to but cannot implement as ecologists (Diaz et al. 2003). Thus, the urban landscape itself provides the experimental setting within which to investigate questions relating to ecological theories and phenomena (McDonnell and Pickett 1990). In past research, particular attention has been focused on the effects of urbanization on population and community dynamics, ecosystem dynamics (including C storage and nutrient cycling), landscape-level patterns and processes, and the role of invasive species in altering ecological patterns and processes. Additionally, urban soil ecology provides an excellent avenue for public outreach, as this research occurs in the immediate places where we live, work, and play (Miller and Hobbs 2002). However, there is much to still to learn about urban ecological systems and their interaction with sociocultural systems from studying urban soil ecology. We highlight the following five topics where future work is likely to yield important insights to link ecological theory, improved understanding of the urban environment, and the sustainable management of urban soils.

Comparative urban ecology

It is imperative that we broaden our knowledge of different urban places. In essence, a large-scale biogeographical research program is needed to investigate and compare patterns of urban soils and urban ecosystems across different biomes and ecoregions. Two hypotheses could be tested with such research: (1) that urban soils in different locations exhibit great heterogeneity because of the unique sets of interacting human and biophysical variables at different locations; or (2) the similarities of urbanization processes across regions leads to homogenization of soil properties (Pouyat et al. 2002; Pouyat et al. 2003; Grimm et al. 2008b). Conceptual support for the first hypothesis is given by Kaye et al. (2006), who posit that urbanized ecosystems are primarily shaped by unique anthropogenic shifts in environmental control points that determine locally distinct ecological characteristics. How these urban control points will manifest themselves ecologically is likely to differ across different biomes and ecoregions as urbanization processes interact with the natural 'templates' that cities grow within (Pouyat et al. 2006). Preliminarily we know for example that varying as simple a variable as the size of a city can have important implications for soil characteristics and biogeochemical cycling (Pavao-Zuckerman and Coleman 2005; Pouyat et al. 2008). In this issue, Pouyat et al. make predictions for global patterns of soil C storage based upon the interaction of climate, biome, and the nature of urban form and land use. A push to generate long-term data sets collected across many ecoregion types with common methods will help build our understanding of the global biogeography of urban soils.

Drivers of urban soil biodiversity

A growing number of studies have documented the impacts of urbanization on biodiversity patterns and interactions among organisms (McKinney 2002; Faeth et al. 2005; Shochat et al. 2006; Marzluff and Rodewald 2008). Yet, few studies have focused on soil biota so that little is known about urban soil biodiversity (Byrne 2007). However, insights generated to date inspire questions for future research related to ecological theories regarding food webs, relationships between biodiversity and ecosystem function and services, and especially the role of spatiotemporal heterogeneity of environmental variables in shaping urban soil communities (Fig. 1). Most generally, soil biodiversity patterns across urbanized environments are likely to reflect aboveground patterns of resources (especially detritus) and physicochemical conditions as largely determined by human control of land cover and habitat structure (e.g. Shochat et al. 2004; Shi et al. 2006; Byrne 2007). In addition, disturbance dynamics, including time since initial urbanization processes (i.e., age of an urban soil) and everyday landscape management practices (e.g., lawn pesticide applications), are predicted to shape communities by affecting dynamics of species' colonization and persistence (Byrne and Bruns 2004; Smetak et al. 2007). Examining such dynamics can be facilitated by categorizing soil species as urban avoiders, adapters or invaders which would permit testing of theories about relationships between environmental variables and species' life history patterns (McKinney 2002; Marzluff and Rodewald 2008). Of these three functional groups, invasive species are likely to have important effects on urban soil food webs and ecosystem dynamics and they may contribute to the homogenization of urban soil biota across regions (McKinney 2006; Szlavecz et al. 2006). In addition, food web dynamics impacted by urbanization are predicted to differ from those seen in non-urban communities through other mechanisms such as human alteration of resources that lead to unique community compositions and trophic cascades (Faeth et al. 2005; Pavao-Zuckerman and Coleman 2007). In addition to testing general ecological theories about biodiversity, as well as those emerging that are specific to urbanized ecosystems (McKinney 2002; Marzluff and Rodewald 2008), understanding of urban soil biodiversity patterns is needed to better guide urban biodiversity conservation (of above and belowground species), restoration projects and the sustainable management of urban soils and the ecosystem services they provide (McKinney 2002; Wall 2004; Byrne 2007; Heneghen et al. this issue). In addition to ecological theories related to the topics listed here, many others would certainly be amenable to testing in urban soils, which would also likely lead to new insights about how humans affect soil biodiversity.

Scaling ecosystem functions and services

When considering effects of urbanization on soil biodiversity and ecosystem functions and services, of particular importance for future work is understanding how we can scale up and extrapolate from point- and patch-scale research to emergent patterns appearing at the scale of an entire city, or urbanized region. One approach to this problem is considering the extent, configuration, and heterogeneity of patch types across the urban landscape, with emphasis on the role that human modifications within the built environment will have on the locations of control points within biogeochemical systems (Kaye et al. 2006; Kaye et al. 2008). It is important to note that scaling relationships for soil properties within urban ecosystems have been shown to be different than corresponding non-urbanized land uses (Jenerette et al. 2006). Pouyat et al. (2006) point to the importance of considering both built and pervious parts of urbanized ecosystems when thinking about ecosystem processes at coarse scales. With these approaches, our ability to move from point/patch-scale research to that of larger portions of the urban landscape will likely improve. However, as Byrne (2007) suggests, site-specific mechanistic studies of soil processes provide the foundation for studies that examine larger scale patterns in urban ecosystems; for example, studies of N cycling in lawns have led to insights about the watershed scale of N-retention in some cities (Groffman et al. 2004b; Raciti et al. 2008). Focusing study on site-specific control points with a habitat structure framework in mind also has management implications since local landscape patches (or parcels) represent the scale at which landscaping decisions and activities ultimately determine localized biogeochemical processes (Kaye et al. 2006; Byrne and Grewal 2008).

Soils in urban ecosystem management

Enhanced understanding of the role of soils in urban ecosystems can lead to improved management of urban ecosystems for the provision of ecosystem services and the promotion of human health. Importantly the generation of small-scale landscape context and environmental heterogeneity (see Fig. 1) will require site-specific soil ecological knowledge for the management of urban soils and urban ecosystems (Heneghan et al. 2008). Thus, site specific management issues in a parcel within a particular environmental and urban context will necessitate the pairing of soil scientists and ecologists with environmental managers and restoration practitioners. There is a need to balance generally applicable approaches, guidelines, and frameworks with the site-specific needs for urban soil and environmental management.

One avenue to link local and city and region wide management is to further develop the concept of soil quality for urban ecosystems. Assessment of soil quality can be made to better understand ecosystem health, in the sense that the health of an ecosystem can tell us something about the ability of the city to provide ecosystem services or how this ability is impaired. Thus, schemes for describing and assessing soil quality must be designed with the particular use of soil in mind, essentially asking, soil quality for what purpose or ecosystem service (Carpenter et al. 2001; Vrščaj et al. 2008). The concept of soil quality comes from descriptions of agroecosystems and forestry, and while there may be some overlap between the goals of these activities and urban systems, productivity is not the sole ecosystem service we are interested in managing urban ecosystems to provide (Beckett et al. 1998; Bolund and Hunhammar 1999; Alberti 2005; Vrščaj et al. 2008). Specific assessment protocols can be developed that move beyond a broad minimum data set type of analysis, and assess soil properties related to specific functions. For example, Poggio (2008) propose a simple method to asses risk of exposure to heavy metal polluted soils that integrates land use characteristics that should prove useful for guiding remediation decisions in urban environments. The development of assessment approaches that are designed with the generation of high information content, utility, ease of application, and tight linkage between assessment and recommendation are essential for the successful translation of soil ecological knowledge into the decision making and management that promotes soils for human and environmental health in urban ecosystems.

Interdisciplinary approach to urban soil ecology

Finally, we need an urban soil ecology that steps outside of the comfortable box of traditional biodiversity and biogeochemistry research and fully embraces the value of including sociocultural variables in the examination of urban environmental patterns (Hope et al. 2003; Redman et al. 2004; Grimm et al. 2008b). Stronger connections with social sciences will provide deeper insight into the drivers of urban soil changes (Fig. 1) and corresponding pathways to target management and mitigation toward. For example, adopting a perspective for urban soils that draws from political ecology would give us many insights into the particular and specific decisions made at the individual, aggregated, and institutional levels that drive the process of urbanization (Robbins et al. 2001). Peterson (2000) suggests that integrating political ecology with concepts of ecological resilience (Holling 1973; Gunderson and Holling 2002) might provide a suitable broad conceptual framework for understanding urban soils, given the potential for alternative stable states, and importance of thresholds for change that come about due to human action and management. In addition, linking environmental perception, drivers and constraints of urban landscape management choice and action, and an understanding of the spatial heterogeneity of urban soils would provide a more meaningful understanding of the mechanisms by which ecosystem services and disservices are generated in urbanized environments (Byrne and Grewal 2008).

Theoretical perspectives that integrate ecological and social sciences have seen little application to urban soils, but offer a wealth of improved understanding of urban ecological systems. Strong connections exist between the two perspectives that when integrated within urban ecosystem management and ecological restorations they serve as a means to engage in citizen science, outreach, education (Light 2003). To further increase dissemination of knowledge about urban soil ecology and sustainable urban soil management, soil ecologists could engage in public education and outreach programs, similar to those used by university extension agents use to communicate with farmers about agroecosystems. This would represent an exciting new dimension for a career in soil ecology that would simultaneously promote wider understanding about both soils and urbanized ecosystems.

Conclusions

Although foundational work has been established, it is clear that we have only "scratched the surface" in terms of understanding the effects of urbanization on soils and their ecology. Clearly more investigations and experiments will lead to new insights about soil ecology in general and the effects of urbanization on ecosystems (Grimm et al. 2008b, Pickett et al. 2008). The conceptual model we present and insights generated by the papers in this special issue can serve as guides to "digging deeper" into urban soil ecology through research that integrates ecological theory with its application to societal needs for the sustainable management of urbanized ecosystems and the valuable ecosystem services provided by their soils (DeKimpe and Morel 2000; Wall 2004).

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