Urban Soils

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Introduction

Urban soils are notoriously challenging to categorize. In the compendium of soil surveys produced by the U.S. Natural Resource Conservation Service (NRCS), formerly known as the Soil Conservation Service, soil series in urban areas are often identified on soils maps with the broad designation of 'Urban Land Complex' (Schever and Hipple 2005). In cities, the vertical, in-place pedogenetic processes that form soil (Jenny 1941) are episodically disrupted by cut and fill operations during urban development. Time, as a major factor of soil formation, is constantly cut short, and soil formation processes are continuously reset. Also, with the rampant redistribution of topsoil and subsoil that occurs in the development of housing additions, streets, office buildings, industrial areas, and infrastructure such as pipe and powerline networks, one cannot be certain where and how a given soil developed (Amossé et al 2015). If one digs a soil pit in an urban area, the soils encountered might either have occurred naturally through long-term pedogenesis processes, or they might have been transported there from somewhere else, perhaps even from outside the local region. As a result, soil scientists and managers have long been uncertain as to how to either classify or characterize urban soils.

Healthy soils in cities are essential to the functioning of healthy urban ecosystems. Infiltration of precipitation into soils is a natural part of the hydrologic cycle; without sufficient infiltration either due to surface sealing or to removal of adequate soil volumes, urban streams become flashier with higher flood peaks (Yeakley 2014). Soils also filter pollutants; without sufficient contact with soil, runoff waters will contain higher amounts of chemical contaminants including metals, hydrocarbons, excess nutrients, pharmaceuticals and personal care products (Wessolek et al 2011). Soils provide substrate for vegetation and the faunal communities that inhabit vegetation (see Chapter 32); with inadequate amounts and quality of soil, urban areas are left susceptible to invasive vegetation and a general poverty of plant communities. Such diminishment of vegetation leads also to a reduction of wildlife habitat in the urban environment, and taxa such as birds, mammals, and insects become dominated primarily by those animals adapted to urban environments. Vegetated areas in urban environments also mitigate the urban heat island effect; without sufficient soil to support sufficient vegetation canopy, the problem of urban heat is further exacerbated (see Chapter 11).

From an ecosystem services (i.e. human) perspective, the overall value of soils in urban areas spans all dimensions: provisioning, supporting, regulating and cultural (Dominate et al 2010, Ervin et al 2012). Regarding provisioning, soils in and of themselves are a commodity; topsoil is sold in nurseries, and subsoil is used for fill material by construction companies during urban development. Additionally, soils contribute vital supporting services, including water, nutrient and carbon cycling as well as habitat for vegetation, fungi, bacteria and both vertebrate and invertebrate animals (Guilland et al 2018). Another valuable set of ecosystem services coming from soils are in the regulating category, including flood mitigation, filtering of contaminants,

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biological control of pests, and storage of carbon (Groffman et al 2003). Finally, soils provide cultural ecosystem services by retaining connections between people and the natural environment (Figure 17.1), spanning human health, recreation, urban agriculture, and urban wildlife (McClintock 2010, Li et al 2018). In essence, soil provides a vital substrate that supports the recreational and spiritual experiences people have with nature while living in cities.

[INSERT FIGURE 17.1 ABOUT HERE]

Factors of Urban Soil Formation

As first described by Jenny (1941), the formation of soil involves several complex factors, summarized by the acronym CLORPT, where CL = climate, O = organisms, R = topography, P = parent materials, and T = time. In urban settings, several of these factors are altered. Climate is affected by the urban heat island effect (see Chapter 11), causing warmer temperatures in the more intensely urbanized parts of the city that likely accelerate soil formation processes. The presence of organisms is affected by reduced areas of naturally formed vegetation and fauna, and by much greater densities of humans and urban adapted wildlife. A reduction in vegetation density would slow soil formation processes, while an increase in human density has many effects on soil, as discussed in the next section. Topographic factors are changed, with some leveling of planform during development as well the removal or constriction of natural features such as meandering stream channels that affect soil formation and distribution. Parent materials are largely unchanged by urbanization, although they may be more exposed by excavation in places, while soil profiles themselves may be underlain by previously deposited trash and debris that may introduce exotic materials (Asabere et al. 2018). The soil formation factor that changes most dramatically in urban areas, however, is time.
As humans develop an urban area, which can happen both over centuries as well as over a compressed period of months or years through rapid urban growth, the soils are repeatedly altered, in many striking ways. As Jenny (1941) and many subsequent soil scientists have found, pedogenesis (i.e. soil formation) typically takes decades to centuries to occur naturally. In urban areas, however, these long-term soil formation processes are constantly interrupted as roads are constructed, deep foundations are dug to create buildings, residential neighborhoods are excavated, and waterway access and port facilities are created. Every built structure minimally requires removal of the upper horizons (i.e. O and A horizons) of a typical soil profile, and often further requires the removal of a large volume of subsoil (i.e. B and C horizons). The foundations of built structures often require the import of subsoil, often from nearby landscapes within the city. This process of removal and redistribution of soils, often termed "cut and fill," scrambles the naturally vertically oriented pedogenesis process, and after repeated cases of cut and fill, it is nearly impossible for soil scientists to determine the origin of a given soil.

Nevertheless, once the built environment of a given urban landscape has been established, the soil formation processes described by Jenny (1941) all swing back into action, including time. Mineral surfaces within the soil matrix begin again to be affected by weathering processes driven by rainfall acidity (due to carbon dioxide concentration as well as other constituents depending on local air quality) and by organic acids provided by vegetation that is either purposefully planted by humans (e.g. lawns and gardens) or begins again to grow on what exposed soil remains (i.e. weedy plant species). It also follows that effects of climate continue to influence decomposition and weathering, although perhaps at a faster rate than elsewhere due to urban heat, and that topography and parent materials continue to help shape soil formation. If left alone long enough, i.e. if the built landscapes remain unaltered such as in residential neighborhoods that are essentially unchanged for many decades or longer, then time as a soil formation factor asserts itself as well. Humans, however, tend to continue to manipulate their soils in urban areas far more often than would be found in comparable natural areas, via maintenance of lawns, exotic plants, gardens and park areas (Figure 17.2). As such the soil formation factor of time in urban areas is continuously cut short, and the process of soil formation is constantly interrupted.

[INSERT FIGURE 17.2 ABOUT HERE]

Soil Alterations in Urbanizing Areas

Development of the built urban environment has a profound impact on the soil. At the most extreme, such as in the construction of buildings and major roads, the soil is removed and effectively eliminated altogether. The footings required for such structures may be tens of meters deep, consisting of materials such as rock, rebar, and concrete, with little to no possibility that soil formation will re-establish soil in those locations. In the case of road construction, the impact on soil can be measured in the tens of kilometers longitudinally and up to a hundred meters laterally, for each road constructed. As a result, urban areas are strongly characterized by a large percentage of impervious area, in a general process that has been termed surface sealing (Charzynski et al. 2018).

These large-scale construction efforts remove massive volumes of subsoil, which are then redistributed, often on nearby low-lying areas in and near the city during development. This process of "cut and fill" results in a key feature of urban soil patterns: the widespread presence of subsoil on the surface. As residential areas develop, moreover, the process of cut and fill is essential both to create residential roads at low elevation and to establish topography for houses and apartment buildings at higher elevations so that they drain towards roads, and also to associated storm drainage systems.

Typically, the subsoils removed during road construction form the primary substrate for residential lots; as such the topsoils in residential developments are either removed or covered by subsoil, resulting in residential yards with fairly poor quality soil texture, often with higher percentages of finer particles, i.e. clay and clay loam. Subsequent application of sod for turf development of the urban lawn improves soil quality only for a few centimeters depth. This general characteristic extends beyond residential lawns to other surface features such as median strips in roads and unpaved areas between commercial buildings and roads.

Urban areas typically retain a considerable amount of land that does not have either commercial or residential construction, such as urban parks and greenspaces. In these areas, the character of the soil ranges widely from relatively unaffected to severely disturbed. The impacts are often the result of dumping of soils that were removed during construction processes, and again are mostly characterized as subsoil. In the greenspaces where soils were not affected by cut and fill spoils, other urban impacts may also occur, due to recreational use by both vehicle and foot traffic, and thus, even in areas such as urban forests and urban riparian areas, soils are often more compacted than one would find in a similar environment in a rural area. Additionally, all urban soils including those in urban parks and greenspaces are subjected to higher levels of contaminant deposition via both dry fallout and rainfall, including higher levels of metals, hydrocarbons, and aromatic compounds (Pouyat et al 1995).

Urban Soil Characteristics

As a result of the various land uses in urban areas, urban soils vary widely. Of all soils, those found in parks and greenspaces have the best chance to be in a natural state of more advanced soil formation, with deeper topsoil horizons, less compaction, more organic matter and high levels of native flora and fauna. On the other extreme, soils found in densely urban areas of high percentages of total impervious area and industrial land uses tend to lack topsoil horizons, be highly compacted, have less organic matter as well as less native flora and fauna (Moriyama and Numata 2015). In between those extremes, soils in residential areas have highly variable states, ranging from relatively impervious, low diversity urban lawns to ornamental and vegetable gardens with imported but high levels of organic matter and high plant and animal diversity, albeit composed of often exotic and non-native species.

Due to the wide variety of alterations and land uses to soil in urban areas, it is then challenging to discuss general characteristics in urban soil. Soil formation processes are constantly interrupted, particularly in urban areas where new buildings, residences, roads and infrastructure are being constructed. Topsoil is often missing or buried or in an early stage of formation. Soils existing at a given site may have been deposited there from another location, either from nearby or from an entirely different location many kilometers away. Due to increased levels of traffic, urban soils are usually more highly compacted, even in parks and greenspaces. As a result, urban soils are less permeable and runoff response to rainfall tends to shift to more flashy streamflow, with higher peak flows (Yeakley 2014).

In comparison to soils in rural areas, urban soils on the whole have less organic matter; this occurs in part due to thinner topsoil and in part due to an overall reduction in plant litter, as vegetation density is generally lower and decaying vegetation matter such as fallen leaves are less often allowed to decompose in place. An exception to this condition occurs in urban gardens and in areas of ornamental shrubs near residences and buildings, where residents provide mulch, peat and other organic matter from sources external to the site (Vodyanitskii 2015). Lower levels of organic matter lead to lower amounts of organic acids in the soil, which leads to higher soil pH levels (Jim 1998). As a result, urban soils tend to be more basic chemically, and the process of soil development is slower.

Urban soils often have levels of biota that are lower than those found in rural areas. This condition arises partly because of thinner top soils and lower organic matter, and partly due to the higher levels of compaction in urban soils. An additional factor that constrains soil biota in urban areas is the larger application of pesticides, which typically target both weedy plant species and herbaceous insects and other fauna. The net result is a less diverse community both of native plant species as well as of native fauna in urban soils.

Management and Restoration of Urban Soil

In considering how urban soils are managed, it is important to recognize the primary human uses envisioned for a given landscape. For example, residential lawns and grassy median strips alongside roads are typically managed to maintain a healthy grass turf, and landscape features surrounding commercial buildings are primarily managed for the success of ornamental shrubs and flowering plants that inhabit them. The few centimeters of sod that supports the grasses in urban lawns typically are a thin veneer, while the active soil in areas of shrubbery is deeper and tends to be managed with regular applications of mulch, which provides more organic matter to the soil. In general, the soil underlying urban lawns and to a lesser extent shrub and flower landscaping is kept in an early stage of pedogenesis, with the soil not allowed to develop more deeply and richly as one might find in an undisturbed rural area.

A strong contrast to this general condition of immature urban soils, however, may be found in gardens in urban areas (Logsdon et al. 2017, Tresch et al. 2018). Whether the garden is primarily for flowers or vegetables, here the soil development processes are accelerated. Gardeners typically apply large amounts of organic matter and fertilizer, tilling the ground 15-30 centimeters or more in depth, and accelerating the process of topsoil creation with adequate nutrients and permeable soil textures for water infiltration. Taken as a whole, urban soils are thus quite heterogeneous, with widespread immature soils in lawns contrasting with pockets of well-developed soil profiles in areas of household and community gardens (Kumar and Hundal 2016). With the increased popularity of urban agriculture in cities around the world (Thornett 2016; Chapters 22 and 41), community scale gardens are likely to continue to expand and perhaps tilt the overall soil development balance toward more mature soils in residential areas of cities.

Related to the impact of gardening on urban soil development is the recent advent of soil rehabilitation and restoration efforts associated with revegetation efforts using trees and native plants. On a world-wide basis, tree planting efforts in urban areas have expanded greatly in recent years (Bodnaruk et al. 2017). Trees provide many beneficial ecosystem services to urban areas, including cooling the urban heat island via evapotranspiration, reducing stormwater impacts both via evaporation of canopy-intercepted rainfall and by transpiration of soil water storage, increasing uptake of carbon dioxide, and providing habitat for wildlife. Both private citizen groups, such as Friends of Trees based in Oregon USA, and municipal governments have initiated major campaigns to reestablish tree canopies in many cities globally.

Successful tree planting requires adequate soil, and tree root balls typically need soil amendments with increased organic matter of at least a meter in depth and several meters in diameter laterally. Similarly, some cities have undertaken native revegetation efforts, such as Portland, Oregon in the USA, where greenspaces are targeted for the removal of invasive plants and reestablishment of native plant cover. These efforts have succeeded much better when the soil is vigorously amended in combination with invasive plant removal and native vegetation planting (Oldfield et al. 2014). Full site restoration efforts such as these provide the most promise for mature soil restoration, not just because of the efforts made at the time of vegetation establishment, but also continuing as these native plant communities become established and provide the organisms needed for soil formation over time in the sense of Jenny (1941).

A different category of soil rehabilitation concerns conversion of brownfields by removal of toxic contaminants. These efforts are very intensive and costly, depending on how difficult it is to remove the toxic compounds that might be found at a given site. The goal of these efforts is typically to convert the soils into safe areas for human contact, often with the goal of then constructing building for human habitation and use on these sites. As a result, remediation of soil in brownfields does not always result in the restoration of soil profiles and natural pedogenetic features.

Novel Urban Soil Systems

Humans have gardened in cities for millennia. Urban dwellers have long had the need and the desire to grow plants both for food and for aesthetic reasons. As described in the previous section, such gardens can accelerate soil development processes, provided the gardens are developed on the ground surface and interact with the substrate. Yet people also have a long history of growing plants in pots, thereby extending the distribution of soil in urban areas into a variety of built structures such as artificially-lit basements, window ledges and rooftops on tall buildings. In some senses, then, the idea of novel urban soil systems in cities really is not anything new.

What is new, nevertheless, is the growing proliferation of various types of green infrastructure in cities, much of which has ecosystem-oriented purposes that go far beyond those of flowerpots and traditional backyard gardens. The purposes of green infrastructure span a large range of concerns in urban ecosystems, from storm water management to wildlife habitat. Green infrastructure includes ecoroofs, living walls, bioswales, planter boxes, pervious pavement, and tree trenches, and in all cases soil is involved (Figures 17.3, 17.4). In a strong sense, green infrastructure extends the terrestrial ecosystem functionally into places in the city previously out of reach by the natural environment, and provides ecosystem services that improve the quality of life of urban dwellers.

[INSERT FIGURES 17.3 AND 17.4 ABOUT HERE]

The configuration of the soil in given type of green infrastructure depends on its purpose. For example, a planter box might have a combination of topsoil for growing plants for purposes of evapotranspiration and moderating the quantity and quality of rooftop runoff, overlying a bed of gravel or cobble so that efficient drainage occurs (Figure 17.5). Ecoroofs can be configured to be either extensive or intensive (Oberndorfer et al 2007); an extensive ecoroof has only a thin veneer of soil with hardy plants such as sedums, while an intensive ecoroof might have a meter or more depth of soil profile, with the ability to support large woody vegetation such as small trees and shrubs (Figure 17.6). The purpose of the extensive ecoroof primarily concerns stormwater management, while the goals of the intensive ecoroof are much broader spanning not only stormwater management but also ecological functions such as wildlife habitat, plant diversity, and food production. A noteworthy type of green infrastructure that has value for urban soils is a bioswale (Figure 17.3), or any type of green infrastructure connected to the ground; if a bioswale has no bottom liner, then there is potential for the soil profile to develop naturally in the sense of pedogenesis as set out by Jenny.

[INSERT FIRGURES 17.5 AND 17.6 ABOUT HERE]

Conclusions

While soils in cities remain challenging to characterize, continued studies by urban ecosystem scientists are revealing general characteristics of urban soils. While all soil formation factors as per Jenny (1941) remain in play in urban areas, the factor of time is particularly shortchanged, with urban soils regularly disturbed and soil formation reset, keeping most urban soil in a fairly immature development stage. Additionally, in many places in the city environment, such as lawns, median strips and vegetated landscapes near commercial buildings, topsoil is often either very thin or buried by subsoil or missing altogether. Humans nevertheless have long practiced gardening, even if mostly at an individual or household scale, and in so doing have helped promote mature soil profiles in otherwise rather sterile urban environments. As urban agriculture in cities world-wide increases, there is potential for further maturation of soils in urban areas. Additionally, the advent of novel urban soil systems associated with green infrastructure that support an important range of ecosystem services in urban areas will likely continue to enhance the value of urban soils and to promote higher quality of life for both humans as well as many other species of plants and animals in urban environments.

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Figure 17.1. Street Mural Entitled "Reach High and You Will Go Far" in Philadelphia, PA. Artist: Josh Sarantitis. Photo by JA Yeakley, 2013.

Figure 17.2. Landscape Elements on the Plaza de Mayo, Buenos Aires, Argentina. Photo by JA Yeakley, 2010.

Figure 17.3. Bioswale on the Big Green Block, Philadelphia, PA. Photo by JA Yeakley, 2013.

Figure 17.4. Ecoroof at Kensington High School, Philadelphia, PA. Photo by JA Yeakley, 2013.

Figure 17.5. Experimental Planter Boxes showing Soil Profiles. Experimental planter boxes were tested to determine effects of varying soil mixes on simulated stormwater water retention and water quality; these tests were conducted at Wilsonville, OR, USA. Photo by JA Yeakley, 2009.

Figure 17.6. Intensive Ecoroofs with Tree Vegetation. These ecoroofs were located on high-rise buildings in Vancouver, BC, Canada. Photo by JA Yeakley, 2005.