# A New Perspective on Opportunities for Stormwater Mitigation through Soil Management in Ordinary Urban Landscapes

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## Abstract

Renewed interest in green infrastructure as a stormwater management tool has focused attention on the effects of diverse landscape elements such as urban tree canopy, bioretention facilities, and rain gardens. However, ordinary urban landscapes—such as street medians, grounds of commercial and residential properties, and school grounds—make up much of the nonimpervious surface in urban watersheds and can be managed to increase their ability to receive and store rainfall. We propose that exploiting this potential creates an opportunity for a more holistic strategy for stormwater management where every portion of the landscape performs optimally, rather than solely relying on small, hyper-functioning cells. On average, urban soils are characterized by compacted soil, slow infiltration, and low hydraulic conductivity. Consequently, all such open soil areas are typically assumed to have lower stormwater management potential than their less disturbed rural counterparts. Soil preparation, root distribution, and selection and maintenance of surface treatments such as mulch, however, can strongly affect these characteristics, enhancing the ability of some urban landscapes to capture rainfall. We describe the potential of certain soil and vegetation management strategies to alter this "typical" behavior of urban landscapes. Although some of these practices are acknowledged as best management strategies, many are not or are infrequently implemented. Broader creation and adoption of such Better Management

Practices (BMP) combined with additional research has potential to encourage more optimal management of ordinary urban landscapes to improve water quality.

It is common knowledge that urbanization results in greatly increased impervious cover, but it also strongly affects the characteristics of the remaining soils—and both of these alterations in land surface cover contribute to increased stormwater runoff generation. During typical land development, vegetation is removed, soils are compacted, and some areas are covered by impervious materials. The few soils that are not covered after development are generally highly disturbed, and they become saturated quickly and do not drain well. Thus, in addition to there being more impervious surface, the amount of precipitation captured and stored in the remaining soil and vegetation decreases and runoff increases. In spite of there being considerable interest in parcel-level stormwater management approaches in urban areas (e.g., low impact development) that rely on rain gardens, bioswales, and a variety of other engineered, plant-based installations, little attention has been directed to attenuating stormwater through increasing the ability of landscape soils and vegetation outside of such hyper-functioning systems to support stormwater-related ecosystem services on a wider scale in urban land. We suggest that it is time for more attention to be paid to the soils and plants resident in the myriad unpaved soil surfaces present in the built environment—the ordinary urban landscape—and their potential for mitigating stormwater runoff in urbanized watersheds.

## Urban soil surfaces may act like impervious surface

Urban soil needs to support both buildings and green infrastructure (i.e., plant and soil systems that provide various services to urbanites), but these goals require disparate soil physical characteristics: plants need low density soil with fluctuating water and air content, while buildings and roads need the stability of compacted soil. Balancing these two opposing requirements has proven difficult, and soils compacted by traffic and nearby construction activities are frequently encountered in urban areas intended to support plants. Because water may infiltrate compacted soil surfaces slowly, saturation excess occurs rapidly and higher runoff volumes are produced from smaller rain events on urban soils compared to natural, agricultural, or forest soils. In effect, compacted urban soil can act like impervious cover. Indeed, some have suggested that compacted soils be included in definitions of impervious surface (Arnold Jr. and Gibbons 1996; Gregory et al. 2006). At the very least, due to low infiltration rates (Pitt et al. 2008) compacted soils adjacent to impervious surfaces may act as extensions of the impervious surface (Shuster et al. 2005). The effect of impervious areas on watershed protection is so pronounced, it has been suggested as an environmental indicator for natural resource protection in urban planning (Arnold Jr. and Gibbons 1996).

## Poor growth of vegetation in compacted urban soils exacerbates watershed response to urbanization

Compacted urban soils can be difficult to vegetate, and even when vegetated both above-ground growth and root exploration can be considerably restricted (for review see Day and Bassuk 1994). This restriction of vegetative growth can trigger a cascade of site characteristics affecting both the quantity of runoff generated, as well as the quality of this runoff. For example, restricted tree canopy can both impair rainfall interception (Xiao et al. 2000; Wang et al. 2008) and reduce shading that may keep runoff temperatures lower (Jones et al. 2012). Less vegetation generally means fewer organic inputs via root turnover and more litter in compacted soils. Fewer organic inputs result in reduced soil carbon pools (Brevik et al. 2002), a factor associated with reduced hydraulic conductivity (Vereecken et al. 1990) presumably because soil organic carbon also plays a role in the formation and stabilization of aggregates in surface soil layers (Tisdall and Oades 1982). Ultimately, this can affect soil permeability. Although total urban soil carbon increases with time since development (Scharenbroch et al. 2005) and is higher in soils close to roads (Park et al. 2010) and, surprisingly, minor compaction may even protect existing soil carbon and slow its decomposition (Deurer et al. 2012), there is still a dearth of soil carbon in many urban soils. Chen et al. (2013) found that common urban land development practices such as scraping and replacing topsoil depleted total soil organic carbon by approximately 35%, and mineral-bound carbon pools, that are typically expected to be quite stable, by 47%. This is reflected in the reduced carbon stores often found in newly developed land (Scharenbroch et al. 2005). This reduced soil carbon and lack of new organic inputs where vegetation is scarce has potential to impede soil structure development and a return to predevelopment hydrologic characteristics.

In addition, few studies examine soil carbon or aggregation more than 15-20 cm beneath the surface—a zone that is frequently compacted in developed land. The prevalence of grading and the associated soil cuts and fills in modern land development point to a need to address soil properties at depth, and not just in surface horizons. In addition to its effect on soil carbon stores, soil aggregates, and hydraulic conductivity, compaction can reduce root exploration or restrict roots to surface layers—root exploration that might otherwise increase saturated hydraulic conductivity in soils by creating preferential flow paths (Bramley et al. 2003; Johnson and Lehmann 2006; Bartens et al. 2008).

## Better estimates of the effects of soils on runoff generation are needed

Urbanized land surface is generally quantified in terms of its impervious cover rather than in terms of green space, although the two are, by definition, inversely related. As impervious surface increases, “open soil” (which we define as unpaved soil that is intended to be vegetated) decreases. Although this open soil can be a significant part of land cover in suburban environments, the percentage of such open soil can be very small in highly urbanized environments. For example, in Beijing, green spaces of all types only account for 3.7% of the total area of the city (Zhang et al. 2012). In contrast, the suburban community of Rezé, France is characterized by 37% impervious surface and, presumably, 63% open soil (Berthier et al. 2004). In Rezé, it was estimated that open soil contributed an average of 14% of the runoff generated from storm events. The proportion of land devoted to impervious surface, turfgrass, and other landscape plantings (trees, shrubs, perennials) varies widely based on land use and development style. According to Clagget et al. (2013), approximately 28%  of urban land within the Chesapeake Bay Watershed is impervious surface. This same urban land, however, contains 48% of the turfgrass contained within the watershed, suggesting there is considerable open soil even within densely developed areas. Regardless of whether open soils account for a small or large portion of a watershed, there are opportunities for including these soils as part of a holistic approach to stormwater management. Runoff generation from open soil will vary with rainfall patterns, the distribution of open soil within paved or impervious areas, and the degree of impermeability of the soil. Consequently, improving the potential for runoff mitigation in some soils will provide a better return on investment than others. Nonetheless, variations in infiltration rates of urban soils are considerable and, when not accounted for, can lead to significant errors in stormwater estimates (Woltemade 2010). Thus, better estimates of the hydrologic characteristics of urban soils, their extent, and distribution are needed in order to fully interpret the potential benefits that could be realized through soil management.

Nonetheless, reduced soil permeability is associated with disturbance and construction activity (Gregory et al. 2006), and it is therefore reasonable to assume that the remaining soils in densely-paved and built-upon environments are likely to be more impermeable on average than those in less-densely built environments. An opportunity therefore exists to bring about a notable increase in the potential of soils in dense urban areas to receive stormwater through management efforts aimed at reducing compaction and creating opportunities for greater carbon stores, root growth, and soil aggregate formation. This can be achieved through more aggressive soil rehabilitation efforts during renovations and plantings, as well as design that reduces the likelihood of recompaction. There is an added benefit in addressing impermeable urban soils, however. Precisely because these soils are often intermixed with paved areas, they could—if they were permeable—reduce *effective* impervious surface. Effective impervious surface excludes isolated impervious surfaces that are disconnected from the storm sewer system by adjacent pervious areas, reducing their impact on stormwater generation (Shuster et al. 2005). For example, a residential patio surrounded by lawn would not be included in estimates of effective impervious surface. However, this proximity to impervious surfaces makes the hydrologic function of the lawn that much more important. Consider a paved impervious surface adjacent to a nearly impermeable, compacted, open soil area. In this scenario, runoff can move from either the paved area to the soil or vice versa and there will be little or no infiltration. On the other hand, if the soil area were made permeable, little runoff would move from it to the paved area and if, instead, water flow was directed from pavement to the open soil, then runoff from the paved area would also be reduced for smaller storm events. “What if” analyses estimating potential effects of increases in soil permeability would help characterize the potential of soil improvement practices for a given watershed.

## Soil surface treatments are overlooked as a water quality improvement strategy

Ornamental mulches are typically used primarily for their aesthetic qualities, with decreasing weed competition and maintaining soil moisture as peripheral benefits. In agricultural and construction settings, mulches may also be used for erosion control and prevention of soil crusting, but typically non-ornamental mulches, such as crop residues, are employed for those purposes. In an urban setting, however, choice of ornamental mulch type and placement can have significant effects on the ability of open soil to mitigate the effects of urban runoff. This was demonstrated in a series of recent studies at Virginia Tech evaluating eight different mulch treatments (Mitchell 2014). For example, mulches influenced the speed of runoff generation and suspended solids concentration in runoff. Geotextiles, frequently used beneath inorganic and also some organic mulches, may be useful for extending the life of trafficked gravel surfaces, but their use as a separator between mulch and soil in trafficked areas also leads to more runoff than if the fabric were omitted. Wood chips, in contrast, are relatively unaffected by trafficking and are effective at slowing runoff both before and after being subjected to traffic. Wood chips, for example, could be employed to create intentional paths for pedestrians within a landscape or lawn area rather than the all-too-common practice of allowing bare soil paths to form in struggling stands of turf. While mulches may not protect soils from further compaction due to traffic or equipment, they do slow stormwater runoff, decrease sediment loss, and if organic mulches are used, can improve soil quality over time. Finally, just like soils, mulch materials have different particle size distributions that affect a host of factors, such as water holding capacity and tortuosity of paths for water through the mulch—that in turn can affect stormwater mitigation potential. Consider, for example, the wide range of physical characteristics represented by pine straw, pea gravel, and shredded hardwood bark. Although more study is needed in this area, it seems reasonable that mulches could be selected and applied for specific stormwater mitigation purposes.

In addition to reducing stormwater flows, mulches have potential to reduce sediment loading in runoff. Because highly disturbed soils are difficult to vegetate, they are frequently bare and compacted. In our recent studies at Virginia Tech, compacted soil generated runoff with a total suspended solids concentration five times higher than mulched soils during a simulated rain event.

On the other side of the coin, in areas where rainfall is frequent and soil moisture not often depleted, mulches could potentially increase runoff generation due to the reduced evaporative loss (Adams 1966; Mitchell 2014) between storm events (i.e., greater soil water content leads to less potential for additional water storage). However, most of the eastern USA experiences strong but infrequent storms, allowing even mulched soils to dry. And, perhaps more important than rainfall patterns, if both more permeable soil (described below) and surface covers are maintained, ordinary urban landscapes would be expected to support extensive root systems from trees or other vegetation depleting water from beneath mulched surfaces. Thus, in our judgment, soil moisture would likely be reduced enough that increased runoff from mulched areas is unlikely.

## Increasing permeability of disturbed urban soils

Relatively few studies have focused directly on techniques to restore the hydrologic and biotic functions of natural soil to urban soils, but organic amendments have been a common approach to this goal. Compost as a soil amendment has been studied extensively for its effects on plant growth and health, as well as the physical and chemical properties of the soil. Deep (>20 cm) compost incorporation has been less studied, but has more potential for improving water movement through the soil profile in highly disturbed urban soils which often have compacted zones or hardpans at depth due to grading associated with building. An example of a soil rehabilitation technique that addresses soil compaction below 20 cm is “soil profile rebuilding” (full specification is available online, Day et al. 2012). This technique incorporates compost to approximately 60 cm deep to both increase soil organic matter content and increase pathways for root exploration. In a study that subjected land to the basic scraping and trafficking of typical urban land development, soil profile rebuilding resulted in saturated hydraulic conductivity in these deeper soil regions that was 6 to 11 times greater than untreated soils after 4-5 years (Chen et al. 2014). Furthermore, soil profile rebuilding increases aggregate-protected soil carbon (Chen et al. 2013), tree growth rates (Layman 2010; Mitchell 2014), and may also encourage deeper rooting by trees (Layman 2010). For example, a version of this technique (only to 30 cm depth, rather than 60 cm) was employed in street medians in Arlington County, Virginia and resulted in reduced tree mortality and increased tree growth over standard installation approaches (Mitchell 2014). In this case, new medians were being installed as part of a traffic-calming project and soil profile rebuilding was a cost-effective way to address the challenges of planting in soils that had previously been beneath a major roadway. Although the cost-benefit of these practices has not been examined, addressing soil compaction will result in the cascade of benefits described earlier that are associated with healthy vegetation and potentially reduce the need for landscape inputs such as irrigation to maintain plant health. Thus soil rehabilitation has potential to have profound and enduring effects on stormwater mitigation through facilitating ongoing carbon inputs, creating preferential flow paths for stormwater, and other benefits associated with vegetation.

## Conclusions

The development of stormwater BMPs has partially decentralized stormwater management. Bioinfiltration BMPs of various stripes now mitigate runoff at the parcel- or site-level instead of the city or district level. However, most BMPs still focus on concentrating runoff from a given area and may or may not address the site's runoff production holistically. If all urban land could function at a higher level of ecosystem service provision, stormwater management could become dispersed to utilize every tree and non-impervious surface in a city more effectively, possibly lowering maintenance requirements of hyper-functioning stormwater BMPs, while simultaneously increasing a wide array of vegetation- and soil-associated ecosystem services. Facilitating this transformation requires additional research concerning the extent and distribution of impermeable soils, as well as the magnitude of stormwater mitigation benefits achieved through attention to soils and soil surfaces. However, although far from typical practice, methods of land development or treatment of existing urban soils can already incorporate the goals of increasing soil carbon and reducing compaction and consequently have potential as a tool for achieving improved soil quality for plant growth and stormwater management. Compacted soils can be rehabilitated to become more permeable and to retain that permeability over time. Furthermore, surface treatment choices such as mulches, can affect both sediment transport, surface infiltration, and in some instances show promise for protecting soils from further compaction. Dispersed stormwater management via low impact development (LID) practices has become more popular, but such practices still rely on draining parcels to certain defined areas. If large proportions of the existing landscape can be returned to near pre-development conditions in terms of stormwater capture, stormwater handling LID and traditional stormwater control measures could be reduced for small to medium rain events.

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