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Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity

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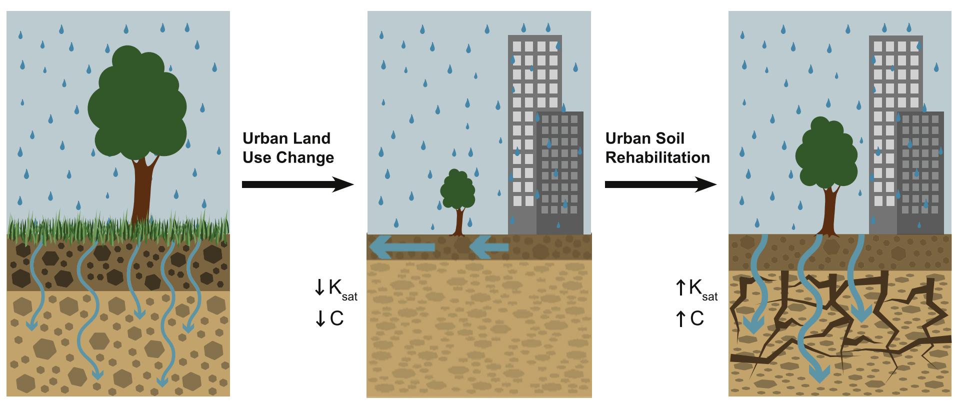
HIGHLIGHTS

- Urban land development reduces soil macroaggregates and permeability.
- Can subsurface soil rehabilitation with compost mitigate these effects?
- Soil rehabilitation does not measurably enhance aggregate formation within 5 years.
- Soil rehabilitation does improve subsurface hydraulic conductivity.
- Urban soil ecosystem service provision is strongly management dependent.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban land use change is associated with decreased soil-mediated ecosystem services, including stormwater runoff mitigation and carbon (C) sequestration. To better understand soil structure formation over time and the effects of land use change on surface and subsurface hydrology, we quantified the effects of urban land development and subsequent soil rehabilitation on soil aggregate size distribution and aggregate-associated C and their links to soil hydraulic conductivity. Four treatments [typical practice (A horizon removed, subsoil compacted, A horizon partially replaced), enhanced topsoil (same as typical practice plus tillage), post-development rehabilitated soils (compost incorporation to 60-cm depth in subsoil; A horizon partially replaced plus tillage), and pre-development (undisturbed) soils] were applied to 24 plots in Virginia, USA. All plots were planted with five tree species. After five years, undisturbed surface soils had 26 to 48% higher levels of macroaggregation and 12 to 62% greater macroaggregate-associated C pools than those disturbed by urban land development regardless of whether they were stockpiled and replaced, or tilled. Little difference in aggregate size distribution was observed among treatments in subsurface soils, although rehabilitated soils had the greatest macroaggregate-associated C concentrations and pool sizes. Rehabilitated soils had 48 to 171% greater macroaggregate-associated C pool than the other three treatments. Surface hydraulic conductivity was not affected by soil treatment (ranging from 0.4 to 2.3 cm h^{-1}). In deeper regions, post-development rehabilitated soils had about twice the saturated hydraulic conductivity (14.8 and 6.3 cm h^{-1} at 10–25 cm and 25–40 cm, respectively) of undisturbed soils and approximately 6–11 times that of soils subjected to typical land development practices. Despite limited effects on soil aggregation, rehabilitation

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that includes deep compost incorporation and breaking of compacted subsurface layers has strong potential as a tool for urban stormwater mitigation and soil management should be explicitly considered in urban stormwater policy.

1. Introduction

By 2030, urban land cover will increase by 1.2 million km^2, nearly tripling the global urban land area extant in 2000 (Seto et al., 2012). As part of the initial disturbance resulting from conversion of rural land to urban land uses, soils are typically degraded by a wide range of modifications including vegetation clearing, topsoil removal, grading, and compaction. These practices adversely influence soil physical characteristics desirable for ecosystem service provision, and consequently urban soils may have increased bulk density (Jim, 1993), disrupted aggregation (Jim, 1998b), and reduced porosity (Alaoui et al., 2011). Ultimately urban soil degradation leads to the loss of critical soil-mediated ecosystem services such as net primary productivity (Milesi et al., 2003), carbon (C) storage (Chen et al., 2013), and stormwater mitigation (Pitt et al., 2008). These and other soil ecosystem services, in particular water-related services, are closely linked to soil structure. For example, soil compaction resulting from urbanization can alter soil aggregate arrangement, pore space, and consequently change soil hydraulic properties (Alaoui et al., 2011). The high proportion of impervious surfaces found in urbanized areas, including the nearly impervious surfaces resulting from soil degradation (Gregory et al., 2006), can lead to flooding downstream, rapidly fluctuating stream levels, and degraded surface water quality (Leopold, 1968; Paul and Meyer, 2001).

Urban soil hydraulic properties have been studied from landscape to aggregate scales. At the landscape scale, several studies report infiltration rate reduction in compacted urban soils (Gregory et al., 2006; Woltemade, 2010). In a simulation study, Berthier et al. (2004) demonstrated that soil (i.e., not paved or covered with other impervious surfaces) contributed an average of 14% of the total runoff volume at the small catchment scale although the per-event percentage varied by storm intensity. There is increasing interest in environmentally sensitive stormwater management practices that take into account the influence of site and soil variables on water movement (Pitt and Clark, 2008). A wide range of best management practices have been developed (e.g., Bartens et al., 2008; Collins et al., 2010; Xiao and McPherson, 2011) including compost amendment application (Olson et al., 2013; Pitt et al., 1999) that aim to alleviate soil compaction and facilitate water movement and storage through the soil profile.

Soil compaction also can influence hydraulic properties in the aggregates themselves, depending on interactions between compaction level, aggregate size and depth (Lipiec et al., 2009). Moreover, the contacts between aggregates control unsaturated water flow (Carminati and Flühler, 2009). Aggregate size distribution can also influence water movement in soils. For example, Abu-Sharar et al. (1987) observed saturated hydraulic conductivity (K_{sat}) reduction resulting from aggregate break down and related macropore loss. In addition to their influence on water flow, aggregates also physically protect soil organic matter (Tisdall and Oades, 1982) and indirectly affect soil C dynamics by regulating microbial activity, water, oxygen, and nutrients in soils (Six et al., 2004).

Soil aggregates are sensitive to management practices (Six et al., 1998), but do have the potential to recover after disturbance (Kay, 1998; Wick et al., 2009a). Management that results in aggregate breakdown may ultimately lead to soil C loss and increased stormwater runoff. Although, Jim (1998a) found that the proportion of water stable aggregates in highly disturbed roadside soils in Hong Kong was very low; to our knowledge no other studies have specifically explored soil aggregate size distribution in urban areas or the response of aggregates to urban disturbance and management practices and subsequent effects on aggregate-mediated ecosystem services.

Because organic material is a significant component of the binding agents that form aggregates (Six et al., 2004), it has been postulated that enhancements to soil aggregation drive increases in soil permeability resulting from compost amendment. Previous studies show that soil organic amendments can improve water holding capacity (Khaleel et al., 1981), increase water retention, especially in sandy soil (Rawls et al., 2003), and produce higher infiltration rates (Boyle et al., 1989; Brown and Cotton, 2011; Martens and Frankenberger, 1992). In urban systems, there is also considerable interest in rehabilitating urban soils with organic amendments to restore some of the ecosystem services diminished during urban land development (Cogger, 2005; Sloan et al., 2012) and compost amendments have been demonstrated to increase C storage (Chen et al., 2013), increase infiltration (Pitt et al., 1999), and improve net primary productivity (De Lucia et al., 2013; Layman, 2010). However, use of a soil amendment is typically accompanied by physical manipulation of the soil to facilitate incorporation and increases in soil permeability may be linked to factors other than increased aggregation. The majority of these studies in urban systems only address surface applications or shallow incorporation of organic amendments (e.g., Cogger, 2005 and Sloan et al., 2012). However, deep tillage accompanied by compost amendment has potential to loosen subsurface soils that are typically compacted during urban development and land use change and thus improve infiltration rates. In addition to its relation to soil structure, organic matter incorporation could also indirectly affect site hydrologic processes through increases in above- and below-ground plant growth. Urban tree canopy cover, for example, can help reduce peak discharge and stormwater runoff (Sanders, 1986) through rainfall interception (Xiao et al., 2000) as well as by increasing the permeability of the soil through root channels (Bartens et al., 2008; Johnson and Lehmann, 2006).

Because of the critical role of soil aggregates in soil hydraulic properties, as well as in protecting soil C and improving soil productivity, restoring soil structure by enhancing aggregation is highly desirable and is the focus of many urban soil management practices that employ organic amendments to rehabilitate degraded soils. Whether and how quickly such rehabilitation can alter soil aggregation processes and effect long-term changes in hydraulic conductivity in soils disturbed by urban development, however, is not known. In our study, we used controlled experimental plots to address the effects of urban land development and subsequent soil rehabilitation on soil structure and permeability. We investigated whether rehabilitating degraded urban soils via deep tillage and compost incorporation plus tree planting can increase soil hydraulic conductivity and if effects are related to changes in soil aggregation or other factors. Soil profile rebuilding (PR) is a technique to rehabilitate degraded urban soils post-development to better support vegetation. In an earlier study (Chen et al., 2013), we found that PR resulted in greater C sequestration including increases to the aggregate-protected C pool, especially in subsurface soils. This suggests that rehabilitation affected the aggregate-organic matter complex, but it is unclear if this is because of improved aggregation, increased aggregate-associated C concentration, or a combination. Thus our objectives were to:

(1) quantify the effects of urban land use development on soil aggregate size distribution, aggregate-associated carbon, and hydraulic conductivity
(2) explore whether post-development soil rehabilitation mitigates these effects
(3) determine the relationship between changes in soil structure and hydraulic conductivity.