Are soils in urban ecosystems compacted? A citywide analysis

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Soil compaction adversely influences most terrestrial ecosystem services on which humans depend. This global problem, affecting over 68 million ha of agricultural land alone, is a major driver of soil erosion, increases flood frequency and reduces groundwater recharge. Agricultural soil compaction has been intensively studied, but there are no systematic studies investigating the extent of compaction in urban ecosystems, despite the repercussions for ecosystem function. Urban areas are the fastest growing land-use type globally, and are often assumed to have highly compacted soils with compromised functionality. Here, we use bulk density (BD) measurements, taken to 14 cm depth at a citywide scale, to compare the extent of surface soil compaction between different urban greenspace classes and agricultural soils. Urban soils had a wider BD range than agricultural soils, but were significantly less compacted, with 12 per cent lower mean BD to 7 cm depth. Urban soil BD was lowest under trees and shrubs and highest under herbaceous vegetation (e.g. lawns). BD values were similar to many semi-natural habitats, particularly those underlying woody vegetation. These results establish that, across a typical UK city, urban soils were in better physical condition than agricultural soils and can contribute to ecosystem service provision.

Keywords: soil compaction; urbanization; greenspace; ecosystem services; urban ecology; land-use change

1. INTRODUCTION

Globally, the human population has become increasingly urbanized, with 50 per cent of people residing in cities and towns, a figure predicted to rise to 70 per cent by 2050 [1]. Consequently, urban areas are growing in extent at a faster rate than any other land use [2]. The importance of urban greenspaces, and particularly the ecosystem services they provide, is gaining increasing recognition as contributors to environmental sustainability and the wellbeing of urban dwellers [3,4]. However, key components of urban ecosystems such as their soils have received little attention.

Soils are the foundation of most terrestrial ecosystem services, storing nutrients and water, providing physical anchorage required for plants to produce food, fuel and fibres. In addition, soils store carbon, play important roles in flood mitigation, purification of water, immobilization of air pollution and provide structural support for buildings [5]. However, many of these functions have been impaired by widespread soil degradation caused by intensification of agricultural and forestry operations. The impact on ecosystem service provision of conversion of semi-natural land into agriculture is relatively well documented. For example, soil compaction, owing to heavy agricultural machinery and livestock trampling, is linked to the degradation of 68 million ha agricultural land worldwide [6]. By contrast, the effects of urbanization on soil physical and chemical properties have attracted little attention and are poorly understood. Urban soils are often thought to be highly modified and of poor quality [7]. There is a widely held assumption that urban soils are highly compacted [7–14], yet there is little quantitative evidence at a citywide scale supporting this assertion which, if correct, would compromise ecosystem service provision. Severe compaction reduces soil pore space, thereby increasing bulk density (BD), which is the mass of a soil sample in a known volume, expressed as grams per cubic centimetre (g cm⁻³). High BD impedes plant growth, increases overland flow of storm waters leading to an increased likelihood of erosion and flooding, and alters biogeochemical cycling [15]. These problems are exacerbated in cities and towns, where the infiltration capacities of soils in greenspaces need to cope with excess runoff from impervious surfaces of buildings and infrastructure, which can cover more than 50 per cent of the urban area [15]. Failure to manage stormwater events in cities can lead to catastrophic economic losses and human distress.

Crucially, there is an urgent need to provide a rigorous assessment at a citywide scale of the influence of urbanization on soil compaction to determine whether the small-scale studies that have found severe compaction in particular locations such as roadside verges (e.g. [8,9]) are representative of greenspaces across an entire urban area. To conduct a citywide assessment of soil compaction, we chose Leicester, UK (population 300 000; area 73 km², of which approx. 42 km² is urban area). T o conduct a citywide assessment of soil compaction, we chose Leicester, UK (population 300 000; area 73 km², of which approx. 42 km² is urban area). To conduct a citywide assessment of soil compaction, we chose Leicester, UK (population 300 000; area 73 km², of which approx. 42 km² is urban area). To conduct a citywide assessment of soil compaction, we chose Leicester, UK (population 300 000; area 73 km², of which approx. 42 km² is urban area). To conduct a citywide assessment of soil compaction, we chose Leicester, UK (population 300 000; area 73 km², of which approx. 42 km² is urban area). To conduct a citywide assessment of soil compaction, we chose Leicester, UK (population 300 000; area 73 km², of which approx. 42 km² is urban area).

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the frequency distributions were otherwise very similar, with both urban and agricultural sites sharing the same modal frequency class of 1.01–1.20 g cm\(^{-3}\) (figure 1b). No significant difference was found between the two BD means for urban and agricultural soils at this depth \((n = 108, t = 0.585, p = 0.810)\).

Land cover exerted a significant effect on BD in urban and agricultural soils \((n = 272, H = 14.828, \text{d.f.} = 6.258, p = 0.02)\). Median arable BD (1.18 g cm\(^{-3}\)) was significantly higher than that in the garden woody, tree and shrub and tall shrub land-cover classes (figure 2). The lowest median BDs were observed in the urban land-cover classes dominated by woody vegetation, including trees and shrubs, in gardens and non-domestic greenspace. Post hoc analysis revealed that, among the agricultural sites, arable soil BD was significantly higher than in pasture. There was no statistically significant effect of depth on BD \((n = 272, H = 1.245, \text{d.f.} = 1.258, p = 0.26)\), nor was there any interaction effect of land-cover class and depth on BD \((n = 272, H = 1.504, \text{d.f.} = 6.258, p = 0.96)\). Neither bedrock type nor superficial deposit had a statistically significant effect on soil BD (see table S1, within the results section of the electronic supplementary material).

3. RESULTS

Urban soil BD at 0–7 cm depth, measured at 136 sites, ranged from 0.26 g cm\(^{-3}\) at a site in the tree land-cover class to 1.41 g cm\(^{-3}\) at a non-domestic herbaceous vegetation site, with an urban mean and median BD of 0.97 g cm\(^{-3}\) \((s.e. = 0.02)\) and 0.98 g cm\(^{-3}\), respectively (figure 1a). At the same depth, the 28 agricultural sites showed less BD variation, ranging from 0.67 to 1.36 g cm\(^{-3}\). The modal BD class was 0.81–1.0 g cm\(^{-3}\) in the urban samples and 1.01–1.20 g cm\(^{-3}\) in the agricultural soils; the later also had a sixfold higher proportion of values in the 1.21–1.40 g cm\(^{-3}\) range (figure 1a). The mean BD in agricultural soils of 1.10 g cm\(^{-3}\) \((s.e. = 0.03)\) was significantly higher than in urban soils \((n = 164, t = 2.987, p < 0.01)\). In the soil samples taken at 7–14 cm depth, the BD of urban sites again showed a wider range of values than in agricultural sites, but the frequency distributions were otherwise very similar, with both urban and agricultural sites sharing the same modal frequency class of 1.01–1.20 g cm\(^{-3}\) (figure 1b). No significant difference was found between the two BD means for urban and agricultural soils at this depth \((n = 108, t = 0.585, p = 0.810)\).
Generally, soil BD values reported in other urban areas, within Europe, the USA and Asia, fell within the range found in Leicester (e.g. [12]). However, as previous urban studies have not used a citywide sample and have generally focused on investigating a limited set of specific land uses (e.g. investigation of roadside soil compaction [8]), there was a tendency for many of the published BD values to be at the higher end of the range reported here. The BD values of arable land in Leicestershire were similar to those reported for the UK and Europe (e.g. [19]), and were higher than the urban soils, probably owing to compaction by agricultural machinery [6].

Urban land-cover class influenced soil BD and was highest in gardens under herbaceous vegetation, possibly reflecting greater compaction from mowing, other garden management practices and more human trampling [20]. The significantly lower values in soils under tree and shrub and tall shrub land-cover classes, in gardens and non-domestic greenspace, are potentially owing to a combination of factors including lower public usage and greater organic material input.

The soils under trees and woody shrubs, with their low-surface BD values, have the greatest potential to contribute to infiltration of storm-waters, thereby reducing flooding frequency and severity, which is an important service provided by urban greenspaces [3]. In the UK, 80 000 urban homes are at risk of flooding [4]. However, the link between specific indicators of soil quality in urban areas and the level of ecosystem service provision is not often made. Urban trees are recognized, possibly owing to broadly held assumptions that urban soils are degraded and functionally impaired. Our findings are an important step in the re-evaluation of ecosystem service provision by urban soils, and suggest that in our study area it is agricultural, not urban, soils that are more degraded by human actions.

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