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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 km^2, of which approx. 42 km^2 is greenspace) as a case study of a mid-sized city within an intensely urbanized region, where cities have been greatly densified in recent years [16]. We hypothesize that soil compaction in urban greenspace will vary significantly with vegetation and land-cover class and will be higher in urban soils than in soils from the agricultural hinterland of the city.

2. MATERIAL AND METHODS

Land-cover classes within Leicester were determined in a geographic information system using the LandBase and MasterMap digital cartographic datasets, supplied by Infoterra and Ordnance Survey, respectively [17]. Urban greenspace was classified into five categories, two in gardens and three in non-domestic land. Random sample sites were generated within each of these categories; a total of 136 sites were sampled across the urban area (please refer to the

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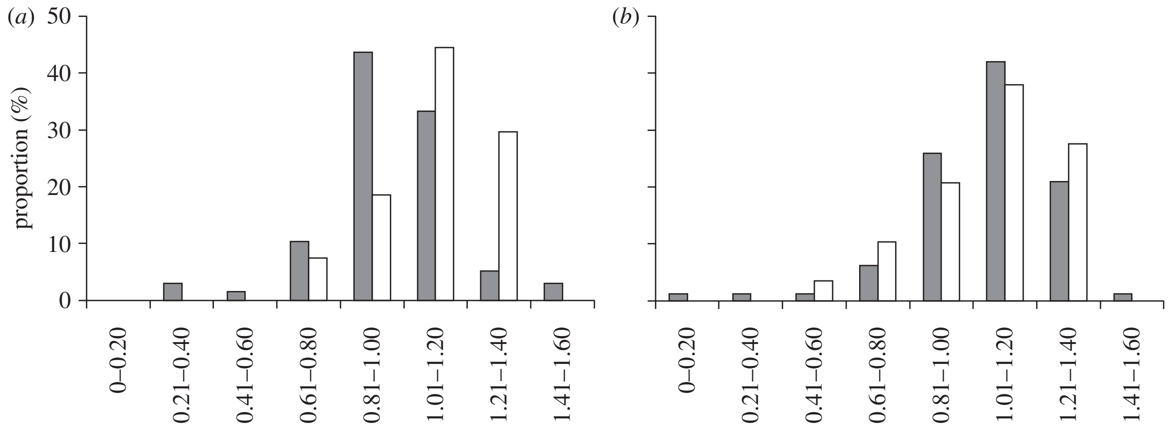

Figure 1. The proportion of samples in soil bulk density classes in urban, grey bars, and agricultural land, white bars, at (*a*) 0–7 cm depth (urban $n = 136$; agricultural $n = 28$) and (*b*) 7–14 cm depth (urban $n = 81$; agricultural $n = 27$).

electronic supplementary material for full sampling strategy). The greenspace was effectively stratified according to vegetation height: in gardens; herbaceous vegetation (mainly lawns; 20% of total greenspace) and woody vegetation (trees and shrubs; 11% of total greenspace); in non-domestic greenspace; herbaceous vegetation (mainly grassland; 46% of total greenspace), shrubs and tall shrubs less than 5 m (7% of total greenspace), and trees greater than 5 m (15% of total greenspace). Agricultural sites were randomly selected from within a 7.5 km buffer zone surrounding the city's unitary authority boundary (covering approx. 450 km^2) and agriculture type was determined on site (pasture or arable; $n = 28$). At each randomly generated point, four soil samples were taken between approximately 0–7 and 7–14 cm depths using a BD corer to derive a site mean for each depth. Soil samples were dried at 105°C for 24 h, weighed, homogenized using a ball mill and then passed through a 1 mm sieve. Fine earth BD was calculated after removing the dry weight of any matter greater than 1 mm, and expressed in grams per cubic centimetre (see the electronic supplementary material for further information regarding the soil sampling and processing methodology).

Independent *t*-tests were performed to compare urban and agricultural soil BD as the data were normally distributed. The BD values within the land-cover classes did not show homogeneity of variance, even after transformation, and were analysed using a non-parametric two-way ANOVA on ranked data (Scheirer-Ray-Hare test) in PASW (v. 18). Significant differences between land-cover classes were identified using Dunn's multiple comparison test. One-way ANOVA were used to analyse the effects of both superficial deposits and underlying bedrock on BD (see the electronic supplementary material for a description of bedrock and superficial deposit types).

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 1*a*). 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 1*a*). 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 1*b*). No significant difference was found between the two BD means for urban and agricultural soils at this depth ($n = 108$, $t = 0.058$, $p = 0.810$).

Land cover exerted a significant effect on BD in urban and agricultural soils ($n = 272$, $H = 14.828$, 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 ($n = 272$, $H = 1.245$, d.f. = 1,258, $p = 0.26$), nor was there any interaction effect of land-cover class and depth on BD ($n = 272$, $H = 1.504$, 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).

4. DISCUSSION

The data presented here, gathered from the entire urban area of a representative UK city, establish that the soils within its urban greenspaces are significantly less compact than those in the agricultural land of the surrounding region. Our findings provide no support for urbanization causing widespread compaction in greenspace, and indicate that compaction is localized and infrequent. The highest BD recorded in the urban sites was 1.46 g cm^{-3}, below the 1.69 g cm^{-3} value that can reduce root growth by 50 per cent [18]. The wider range of BD values recorded in urban versus agricultural soil from the same region might be expected on the basis of the greater heterogeneity of land use, management and inputs in urban areas [14]. The median urban soil BD values were similar to those found in equivalent semi-natural and managed habitats in the UK, including broadleaved woodlands, neutral grasslands and improved grasslands [19].

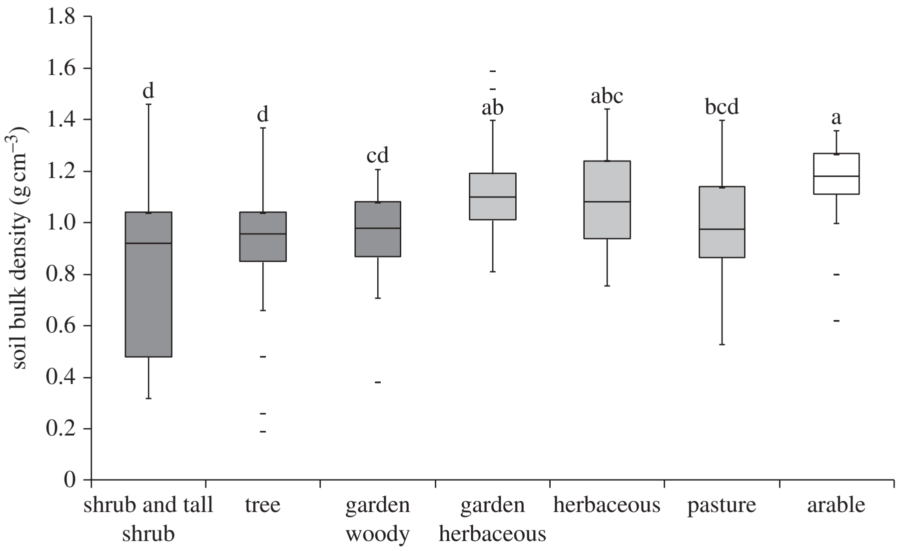

Figure 2. Soil bulk density in urban and agricultural land-cover classes. The horizontal line within the box indicates the median, box boundaries specify the 25th and 75th percentile, whiskers denote the highest and lowest values, lines above or below whiskers indicate outliers.

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 widely recognized to confer economic and environmental benefits through carbon sequestration [21], pollutant interception and air filtration [3] and temperature regulation [22], but insufficient attention has been paid to their role in enhancing soil quality. Protection and enhancement of urban soil quality should be an inherent consideration in local and regional planning. However, this valuable resource is too often overlooked and the range of services soils confer to urban areas and surrounding ecosystems is not recognized, possibly owing to widely 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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1 UN. 2008 *World urbanization prospects: the 2007 revision.* New York, NY: United Nations.
2 Antrop, M. 2000 Changing patterns in the urbanised countryside of Western Europe. *Landscape Ecol.* **15**, 257–270. (doi:10.1023/A:1008151109252)
3 Bolund, P. & Hunhammar, S. 1999 Ecosystem services in urban areas. *Ecol. Econ.* **29**, 293–301. (doi:10.1016/S0921-8009(99)00013-0)
4 RCEP. 2006 *The Urban Environment.* 26th Report. Royal Commission on Environmental Pollution, London, UK.
5 Dominati, E., Patterson, M. & Mackay, A. 2010 A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecol. Econ.* **69**, 1858–1868. (doi:10.1016/j.ecolecon.2010.05.002)
6 Soane, B. D. & van Ouwerkerk, C. 1995 Implications of soil compaction in crop production for the quality of the environment. *Soil Tillage Res.* **35**, 5–22. (doi:10.1016/0167-1987(95)00475-8)
7 Lorenz, K. & Lal, R. 2009 Biochemical C and N cycles in urban soils. *Environ. Int.* **35**, 1–8. (doi:10.1016/j.envint.2008.05.006)
8 Jim, C. Y. 1998 Urban soil characteristics and limitations for landscape planting in Hong Kong. *Landscape Urban Plan.* **40**, 235–249. (doi:10.1016/S0169-2046(97)00117-5)

9 Jim, C. Y. 1998 Physical and chemical properties of a Hong Kong roadside soil in relation to tree growth. *Urban Ecosyst.* **2**, 171–181. (doi:10.1023/A:1009585700191)
10 Banaitis, M. R., Langley-Turnbaugh, S. J. & Aboueissa, A. 2007 Variations of soil organic carbon in three urban parks: a Maine case study. *Int. J. Appl. Environ. Sci.* **2**, 119–128.
11 Lehmann, A. & Stahr, K. 2007 Nature and significance of anthropogenic urban soils. *J. Soils Sediments* **7**, 247–260. (doi:10.1065/jss2007.06.235)
12 Smetak, K. M., Johnson-Maynard, J. L. & Lloyd, J. E. 2007 Earthworm population density and diversity in different-aged urban systems. *Appl. Soil Ecol.* **37**, 161–168. (doi:10.1016/j.apsoil.2007.06.004)
13 Pitt, R., Chen, S., Clark, S. E., Swenson, J. & Ong, C. K. 2008 Compaction's impacts on urban storm-water infiltration. *J. Irrigation Drainage Eng.* **134**, 652–658. (doi:10.1061/(ASCE)0733-9437(2008)134:5(652))
14 Pickett, S. T. A. & Cadenasso, M. L. 2009 Altered resources, disturbance, and heterogeneity: a framework for comparing urban and non-urban soils. *Urban Ecosyst.* **12**, 23–44. (doi:10.1007/s11252-008-0047-x)
15 Scalenghe, R. & Marsan, F. A. 2009 The anthropogenic sealing of soil in urban areas. *Landscape Urban Plan.* **90**, 1–10. (doi:10.1016/j.landurbplan.2008.10.011)
16 Bibby, P. 2009 Land-use change in Britain. *Land Use Policy* **26**, S2–S13. (doi:10.1016/j.landusepol.2009.09.019)
17 Murray, K. J. & Sheill, D. 2003 A new geographic information framework for Great Britain. *Photogramm. Eng. Remote Sens.* **69**, 1175–1182.
18 Hamza, M. A. & Anderson, W. K. 2005 Soil compaction in cropping systems. A review of the nature causes and possible solutions. *Soil Tillage Res.* **82**, 121–145. (doi:10.1016/j.still.2004.08.009)
19 Carey, P. D. *et al.* 2008 *Countryside survey: UK results from 2007*. (*CEH project number: CO3259*). Penicuik, UK: NERC/Centre for Ecology & Hydrology.
20 Robbins, P. & Birkinholtz, T. 2003 Turfgrass revolution: measuring the expansion of the American lawn. *Land Use Policy* **20**, 181–194. (doi:10.1016/S0264-8377(03)00006-1)
21 Nowak, D. J. & Crane, D. E. 2002 Carbon storage and sequestration by urban trees in the USA. *Environ. Pollut.* **116**, 381–389. (doi:10.1016/S0269-7491(01)00214-7)
22 Akbari, H. 2002 Shade trees reduce building energy use and CO_2 emissions from power plants. *Environ. Pollut.* **116**, S119–S126. (doi:10.1016/S0269-7491(01)00264-0)