Published paper

Edmondson, JL, Davies, ZG, McCormack, SA, Gaston, KJ and Leake, JR (2014) Land-cover effects on soil organic carbon stocks in a European city. Science of the Total Environment, 472. 444 - 453. Doi: 10.1016/j.scitotenv.2013.11.025

Science of the Total Environment 472 (2014) 444–453

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Land-cover effects on soil organic carbon stocks in a European city ☆

Jill L. Edmondson [a,*], Zoe G. Davies [a,b], Sarah A. McCormack [a,c], Kevin J. Gaston [a,d], Jonathan R. Leake [a]

[a] Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK
[b] Durrell Institute of Conservation and Ecology (DICE), School of Anthropology and Conservation, University of Kent, Canterbury, Kent CT2 7NR, UK
[c] Centre for Ecology and Hydrology, Bush Estate, Penicuik, Midlothian EH26 0QB, UK
[d] Environment and Sustainability Institute, University of Exeter, Penryn, Cornwall TR10 9EZ, UK

HIGHLIGHTS

- We analyse urban greenspace land-cover effects on soil organic carbon stocks (SOC).
- Domestic gardens held greater SOC concentrations than non-domestic greenspaces.
- Urban greenspace SOC storage exceeded that in regional agricultural soils.
- Differences in greenspace management affect SOC stocks.
- Tree planting may enhance SOC stocks in domestic gardens.

ARTICLE INFO

Article history:
Received 27 March 2013
Received in revised form 24 October 2013
Accepted 5 November 2013
Available online 2 December 2013

Keywords:
Urban soils
Urban greenspace
Gardens
Non-domestic greenspace
Ecosystem services

ABSTRACT

Soil is the vital foundation of terrestrial ecosystems storing water, nutrients, and almost three-quarters of the organic carbon stocks of the Earth's biomes. Soil organic carbon (SOC) stocks vary with land-cover and land-use change, with significant losses occurring through disturbance and cultivation. Although urbanisation is a growing contributor to land-use change globally, the effects of urban land-cover types on SOC stocks have not been studied for densely built cities. Additionally, there is a need to resolve the direction and extent to which greenspace management such as tree planting impacts on SOC concentrations. Here, we analyse the effect of land-cover (herbaceous, shrub or tree cover), on SOC stocks in domestic gardens and non-domestic greenspaces across a typical mid-sized U.K. city (Leicester, 73 km^2, 56% greenspace), and map citywide distribution of this ecosystem service. SOC was measured in topsoil and compared to surrounding extra-urban agricultural land. Average SOC storage in the city's greenspace was 9.9 kg m^{-2}, to 21 cm depth. SOC concentrations under trees and shrubs in domestic gardens were greater than all other land-covers, with total median storage of 13.5 kg m^{-2} to 21 cm depth, more than 3 kg m^{-2} greater than any other land-cover class in domestic and non-domestic greenspace and 5 kg m^{-2} greater than in arable land. Land-cover did not significantly affect SOC concentrations in non-domestic greenspace, but values beneath trees were higher than under both pasture and arable land, whereas concentrations under shrub and herbaceous land-covers were only higher than arable fields. We conclude that although differences in greenspace management affect SOC stocks, trees only marginally increase these stocks in non-domestic greenspaces, but may enhance them in domestic gardens, and greenspace topsoils hold substantial SOC stores that require protection from further expansion of artificial surfaces e.g. patios and driveways.

1. Introduction

Soil plays a major role in the global carbon cycle and is the foundation of terrestrial ecosystems, providing or underpinning most of the ecosystem services from which humans benefit (MEA, 2005). Terrestrial ecosystems store 2110 Pg of carbon, nearly three times the amount in atmospheric CO_2, with 74% of this provided by soils (Lal, 2008; Batjes, 1996). Historically, soil organic carbon (SOC) storage has declined substantially, by approximately 40–90 Pg (Smith, 2008), contributing to anthropogenic CO_2 emissions and soil degradation (Lal, 2008). The main driver of this loss has been land-use change from natural or semi-natural ecosystems to cultivated or highly disturbed landscapes (Smith, 2008; Guo and Gifford, 2002; Vitousek et al., 1997). This loss of SOC has impacts at the global scale through its contribution to anthropogenic CO_2 emissions and,

* Corresponding author. Tel.: +44 114 222 0065; fax: +44 114 222 0002.
E-mail address: j.edmondson@sheffield.ac.uk (J.L. Edmondson).

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http://dx.doi.org/10.1016/j.scitotenv.2013.11.025

at the local scale, through loss of critical soil functions including nutrient and water-holding capacity, aggregate stability, infiltration capacity and resistance to erosion (Lal, 2009). Signatories to the United Nations Convention on Climate Change and the Kyoto Protocol are required to provide inventories of terrestrial organic carbon (OC) stocks in order to monitor changes in storage (Bradley et al., 2005). As a consequence, increasingly accurate estimates of SOC stocks, associated with different land-uses and management, are needed to inform policies and actions that enhance OC storage and minimise future losses of SOC.

Urbanisation is an increasingly important contributor to land-use change globally. Worldwide more than half the human population are urban dwellers, a figure projected to increase to 70% by 2050 (United Nations, 2008). Urban areas are expanding more rapidly than any other land-use type (Hansen et al., 2005; McKinney, 2002; Antrop, 2000; Meyer and Turner, 1992), principally as a consequence of sprawl (driven by the construction of large, low density residential developments) and declines in average household size (driven by increases in longevity, single occupancy of dwellings and divorce rates, and in some regions a growing number of second homes (Lepczyk et al., 2007; Liu et al., 2003)). However, in many European cities sprawl has been constrained by planning policy in recent decades. For example, in the U.K. most new housing development is within urban areas, often on the gardens of existing dwellings (garden grabbing) or other previously abandoned/undeveloped land (Dallimer et al., 2011; Bibby, 2009).

The processes of urban expansion and densification both involve land-use changes that impact upon ecosystem function and service provision (Gaston et al., 2010). Until recently, a major gap in current understanding of urban ecosystems concerns the nature and property of their soils particularly in Western Europe (Lehmann and Stahr, 2007; Byrne, 2007; Effland and Pouyat, 1997), despite the critical role of soil in supporting most urban ecosystem services. However, recent research investigating citywide SOC stocks, beneath both urban greenspaces and impervious surfaces, has demonstrated that urban areas are capable storing much larger quantities of SOC than previously realised (Edmondson et al., 2012). Indeed, average storage across an entire U.K. city (assuming 0 kg SOC m^{-2} storage beneath buildings which cover 15% of the city) was 14.5 kg m^{-2}, to 1 m depth (Edmondson et al., 2012). These measurements contrast with the earlier estimates of SOC in suburban areas in England, which gave a mean value of 6 kg m^{-2}, based on the untested assumption that these areas store half the carbon of agricultural grasslands in the same region (Bradley et al., 2005). Furthermore, these new data reveal that urban SOC stocks are 12% higher than the mean storage value for agricultural grasslands and only 15% lower than the mean storage value for woodlands in the English national SOC inventory (Bradley et al., 2005), necessitating a radical revision of the widely held misconception of low ecological values of urban soils.

SOC concentrations are highest at the soil surface and decrease by a negative exponential function, so that in the urban greenspaces of Leicester 47% of the SOC to 1 m depth was found in the top 21 cm (Edmondson et al., 2012), and values under different land-covers converge with depth. Indeed, no difference was found between SOC concentrations in soil under capped surfaces such as roads or pavements (sidewalks) and soils beneath greenspaces at the same depth, indicating that land-cover effects will be most important in the topsoil (which we define here as 0–21 cm). Topsoil is the most important part of the soil, its properties controlling rates of infiltration, nutrient and water holding capacity and plant productivity, all of which are often strongly correlated with organic matter content (Lal, 2010).

It is against the background of rapid expansion and regional densification of urban areas in Europe, together with the need to establish national inventories of ecosystem carbon stocks that the paucity of data on SOC amongst the different urban greenspace land-covers is of increasing concern. In particular, there are important questions about whether different types of urban greenspace and management options can significantly affect these stocks. Despite the longer history of urbanisation, and the greater proportion of urban land-cover in Europe than in the U.S.A., to date there have been no systematic studies of SOC variation with greenspace land-covers in any Western European cities. The role of urban areas in SOC storage has been more extensively studied in North America (e.g. see Raciti et al., 2012; Churkina et al., 2010; Kaye et al., 2008, 2006; Golubiewski, 2006; Pataki et al., 2006; Pouyat et al., 2002, 2006; Jo and McPherson, 1995). Despite this interest, in North America the effects of land-cover on SOC stocks have also not been systematically studied at a city-wide scale. Without this information the consequences of land use changes for urban SOC stocks remains unresolved and appropriate management of the greenspace resource for this ecosystem service remains uncertain.

Recent studies have shown that land-cover types have major effects on aboveground organic carbon storage in urban vegetation — for example trees accounted for 97% of citywide total in the city of Leicester (Davies et al., 2011). In this study domestic gardens contained only 0.8 kg OC m^{-2} in above-ground vegetation whereas urban trees and woodland stored 28.9 kg OC m^{-2} on non-domestic land (Davies et al., 2011). The extent to which these land-cover class differences are reflected in greenspace SOC storage within urban areas remains unclear. As soils globally store considerably more carbon than vegetation, it is important to determine whether policies to manage aboveground OC storage such as tree planting have positive, negative or neutral effects on SOC stocks.

Here, we provide a detailed assessment of land-cover effects on SOC stocks in urban greenspaces in a European city. We measured SOC storage in urban greenspace land-cover classes across the entire urban area of a mid-sized U.K. city, and also in its immediate agricultural hinterland to provide regional context. As land-cover is likely to have the greatest effect on topsoils (Bell et al., 2011), sampling focussed on the surface layer. The urban greenspaces were divided into domestic gardens and non-domestically owned land, within which land-cover class was characterised by vegetation height and type. We quantified SOC across the greenspace of the entire urban area to produce an SOC budget to 21 cm depth. We map the spatial distribution of SOC across the city using high resolution GIS land-cover datasets to improve understanding of the importance of both small and large patches of greenspaces to storage across the entire city surface. These data were used to test the hypothesis that urban SOC concentration and storage would respond to aboveground vegetation land-cover similarly to the national soil inventory data that indicate higher SOC concentrations beneath trees than grassland (Bell et al., 2011; Bradley et al., 2005). Furthermore, we predicted that urban SOC storage throughout the sampled land-cover classes would exceed storage in regional agricultural fields. This research seeks to improve understanding of land-cover effects on urban SOC storage, in order to inform effective management of multifunctional greenspaces for OC storage.

2. Methodology

2.1. Study area

Our study focussed on Leicester, a mid-sized U.K. city, covering an area of approximately 73 km^2 (as defined by the unitary authority boundary), with a human population of approximately 310,000 (Leicester City Council, 2012), located in the East Midlands of England (52°38′N, 1°08′W) (Fig. 1a and b). The region has a temperate climate, receiving 606 mm of precipitation each year and average annual daily minimum and maximum temperatures of 5.8 °C and 13.5 °C respectively (Met Office, 2009). More than three quarters of land in the East Midlands is used for agriculture, of which arable farming is dominant (Rural Business Research, 2012). The main bedrock types underlying the city are from three groups; the Lias Group (Jurassic), the Penarth Group (Triassic) and the Mercia Mudstone Group (Triassic). Superficial deposits cover a large proportion of the bedrock and are

Fig. 1. The geographic location of a) the East Midlands (shaded grey) and Leicester (shaded black) within England, and b) the outline of the Unitary Authority Boundary of Leicester and the major road network within the city (52°38′N, 1°08′W).

comprised of: alluvium, colluvium, fluvial deposits, glaciolacustrine deposits, and glacial till (Rice, 1968). The distribution of both the bedrock geology and the superficial deposits within Leicester were derived from British Geological Survey DiGMapGB-10 digital data (1:10,000 scale; http://www.bgs.ac.U.K./products/digitalmaps/digmapgb_10.html). Soil types within the city are dominated by deep clays, deep loam and seasonally wet deep clays and loam, according to the National Soil Map for England and Wales produced by Cranfield University. The soil types sampled in the city were: Hanslope, Whimple, Salop, Beccles 3, Ragdale and Fladbury 1.

2.2. Soil survey

A GIS was used to determine the land-cover characteristics of the study area, based on the classification of land-cover polygons by Infoterra and Ordnance Survey within their LandBase and MasterMap (Murray and Sheill, 2003) digital cartographic datasets. Within these datasets vegetation patches and tree canopies were mapped to accuracy of 0.25 m^2. Greenspace across the city was classified into five land-cover classes, three of which, found outside domestic gardens, were effectively stratified by vegetation height (as LandBase data are classified using high resolution LiDAR): herbaceous vegetation (comprising grassland and non-woody plants), shrubs and tall shrubs (including woody bushes and immature trees with a mean height of up to 5 m), and trees (mean height greater than 5 m). Domestic gardens were sub-divided into herbaceous cover (including lawn, flowerbeds, and vegetable patches) and cover by shrubs and trees (including woody bushes, hedges, immature and mature trees).

Previous research has demonstrated that 30–50 randomly generated locations within land-cover types provide good representation of vegetation carbon stocks in a city area (see e.g. Davies et al., 2011), therefore a sample of 45 points was randomly generated across the city within two non-domestic land-cover classes; herbaceous vegetation and an amalgamated class of tree, tall shrub and shrub dominated vegetation. Soil samples could not be taken at a number of points because we were unable to obtain permission to access the area, they were deemed to be unsafe to visit (e.g., along railway embankments, abandoned industrial sites) or consent to sample was refused. For domestic gardens, a street layer was created in the GIS and 45 roads were selected at random. Each of these roads was visited and, if there were residential properties present and authorisation from a householder was granted, soil cores were taken from the back garden of one dwelling per road. Agricultural sites (arable $n = 16$; pasture $n = 12$) were selected randomly from within a 7.5 km buffer zone around the unitary authority boundary of Leicester, and the type of agriculture was determined on site (either arable or pasture).

Each random sample point, in the non-domestic greenspace, formed the centre of a 5×5 m quadrat, within which four replicate undisturbed soil cores were taken using sample rings to enable bulk density to be determined (Soil sample ring kit C, Eijkelkamp, Holland). In domestic gardens, cores were extracted from herbaceous areas within the garden (e.g. lawns, flowerbeds) and/or within the vicinity of shrubs and trees (where gardens contained both land-cover classes cores were taken beneath both herbaceous vegetation and shrubs and trees). In both non-domestic and domestic greenspaces, the samples were taken from three depths: 0–7 cm, 7–14 cm and 14–21 cm. These depth intervals were determined by the specifications of the soil coring equipment, which oversampled, by approximately 1 cm, both above and below an internal 5 cm deep sample ring, in which the undisturbed soil sample was collected. The ability to oversample above the sample ring enabled the removal of any leaf litter layer or lawn turf without disturbing the soil sample. Sampling to a depth of 21 cm was not always possible, as urban soils commonly contain an array of materials including bricks, cement, and slag (Lorenz and Lal, 2009; Norra and Stuben, 2003), as well as stones and tree roots.

2.3. Soil preparation and analysis

Soil samples were dried at 105 °C for 24 h and subsequently weighed. The soil fraction of the sample was homogenised into a fine powder in an agate ball-mill (Pulverisette, Fritsch, Idar-Oberstein Germany); but this process did not breakdown stones or anthropogenic fragments (e.g. metals or plastics) within the sample. The ball-milled sample was then passed through a 1 mm sieve and re-dried at 105 °C. Any material greater than 1 mm in diameter was retained, weighed, and removed from total sample weight in order to calculate fine earth soil bulk density (g cm^{-3}) (Edmondson et al., 2011). The method of soil sample preparation differed from the conventional method, whereby samples are air dried then passed through a 2 mm sieve prior to analysis (Rawlins et al., 2008). However method validation comparing the use of the 1 mm sieve after milling to the conventional protocol involving sieving before milling revealed no significant differences in SOC concentration (mg g^{-1}) or density (mg cm^{-3}) (Edmondson et al., 2012), but established our approach reduced sample handling times and gave lower coefficients of variance between replicates.

Homogenised soils were analysed in duplicate for percent total carbon (TC) in a CN analyser (Vario EL Cube, Elementar, Hanau, Germany). Inorganic carbon (IC) was removed from soil samples following the method used by Rawlins et al. (2008), whereby 10 ml HCl (5.7 M) was added to 2.5 g soil. Samples were centrifuged at 1800 g for 10 min, the supernatant was removed and the soils were dried at 105 °C and CN analysis used to determine SOC concentration. As the soil samples were initially dried to establish bulk density, pH measurements were only made on dried soil by the standard procedure of adding 5 g of soil to 10 ml of deionized water (Hendershot et al., 1993).

A sub-set of samples (n = 80) were selected to measure IC concentrations of soils sampled, selected at random from the entire range of depths. IC concentration was calculated by subtracting SOC from TC measured on sub-samples of the same soil. Using this method we did not detect IC within the top 30 cm of any of the 80 samples, and in deeper samples IC was only found in those with pH > 7.0. All samples taken from across the city and adjacent agricultural land with pH > 7.0 were therefore treated with HCl prior to CN analysis to remove any potential IC.

2.4. SOC stocks

SOC storage (kg m^{-2}) was calculated for each individual soil sample using SOC concentration (mg g^{-1}) and soil density (g cm^{-3}) taking into account the mass of the >1 mm fraction discarded after milling. Mean SOC density at each of the three depths (0–7, 7–14, and 14–21 cm), for each land-cover class was multiplied by the total areas of the relevant land-cover class within Leicester (Table 1) in order to estimate land-cover specific soil carbon stocks. Finally, these values were summed to obtain an estimate of SOC to a depth of 21 cm across the greenspace of the entire city. Soils within Leicester capped by artificial surface, including those within domestic gardens, were excluded from this estimate, as most or all of the topsoil is excavated during the impervious surface construction process (Edmondson et al., 2012). SOC storage estimates are hereafter presented as whole numbers in tables so that the process of scaling up from individual samples to the city-scale can be followed throughout the paper. This should not be taken to imply such a level of accuracy.

The distribution of SOC in urban greenspace in 250 × 250 m grid squares was calculated in the GIS using both the Landbase and Mastermap layers to determine proportions of different land-cover classes within each individual square, and the city-wide distribution at this grid scale. The area of each individual land-cover class was then multiplied by the relevant SOC storage values to produce a city-wide map of the distribution of SOC to gain better understanding of its spatial distribution in a city.

2.5. Statistical analysis

Analyses were conducted using ArcGIS (version 9.3, ESRI), R (version 2.10.1, R Development Core Team, 2009) and PASW (version 18). The effects of land-cover class or soil type and depth on SOC concentration (mg g^{-1}) or SOC density (mg cm^{-3}) were analysed using two-way ANOVA. Where data did not conform to ANOVA test assumptions, even after transformation the non-parametric Scheirer–Ray–Hare test was used on ranked data instead. The Tukey post-hoc test on parametric data or Dunn's multiple comparison test on non-parametric data were used to compare differences ($p < 0.05$) in SOC concentration and density between either land-cover class or depth (Wheater and Cook, 2002; Zar, 1999).

3. Results

3.1. Effect of land-cover type and soil depth (0–21 cm) on SOC concentration (mg g^{-1}) and storage (kg m^{-2})

SOC concentrations (mg g^{-1}) were significantly affected by both land-cover class ($F_{(6, 324)} = 20.6$, $p < 0.001$) and soil depth ($F_{(2, 324)} = 32.5$, $p < 0.001$) (Fig. 2a and b). There was also a significant interaction between land-cover and depth reflecting a decline in SOC with depth in the urban land-cover classes that was not apparent in the arable soils ($F_{(12, 324)} = 1.9$, $p = 0.032$). Urban SOC concentrations varied by a factor of 1.65, and soils under trees and shrubs in gardens had significantly higher SOC concentrations (75.2 mg g^{-1} ± 5.4 S.E.) than all other urban land-cover classes, with the lowest concentration in non-domestic herbaceous greenspace (45.5 mg g^{-1} ± 2.0 S.E.) (Fig. 2a). Arable fields had a significantly lower SOC concentration (mean 29.2 mg g^{-1} ± 1.1 S.E.) than all urban greenspace soils.

The response of SOC storage (kg m^{-2} to 21 cm depth) was similar to that of SOC concentration with significant effects of both land-cover class ($H_{(6, 306)} = 20.9$, $p < 0.01$) and depth ($H_{(2, 306)} = 6.8$, $p < 0.05$) (Fig. 3a and b). Unlike SOC concentration there was no interaction effect between land-cover class and depth on SOC storage ($H_{(12, 306)} = 4.9$, $p = 0.96$). Between 0 and 7 cm SOC storage was significantly greater than in the subsequent two depths (Fig. 3b). However, as with concentration the overall decline in SOC storage with depth was not present in arable soils, where median SOC storage was just over 2 kg m^{-2} for each successive 7 cm depth interval to 21 cm.

Median SOC storage in domestic gardens was significantly higher than in all other urban and non-urban land-cover classes (Fig. 3a). When median values for each depth class were added together storage to 21 cm reached 13.5 kg m^{-2} under garden shrubs and trees. Amongst the other urban land-cover classes there were no significant differences in SOC storage (Fig. 3a). Total median values within the other urban land-cover classes ranged from 9.9 kg m^{-2} in domestic gardens under herbaceous vegetation to 8.6 kg m^{-2} under non-domestic herbaceous vegetation, to 21 cm depth. The agricultural soils under pasture had significantly lower SOC storage density than the domestic garden soils and

Table 1
The areal extent and total number of sample sites in the greenspace land-cover classes within the city of Leicester.

Urban land-cover class	Area (km^2)	Proportion of greenspace (%)	Proportion of the total area of the city (%)	Number of sample sites
Domestic greenspace				
Garden shrub and tree	4.7	11.3	6.4	22
Garden herbaceous	8.4	20.2	11.5	36
Total domestic greenspace	13.1	31.5	17.9	58
Non-domestic greenspace				
Tree > 5 m	6.3	15.2	8.6	42
Shrub and tall shrub < 5 m	3.0	7.2	4.1	10
Herbaceous	19.1	46.0	26.0	38
Total non-domestic greenspace	28.4	68.4	38.7	86
Total greenspace	41.5	100	56.6	144

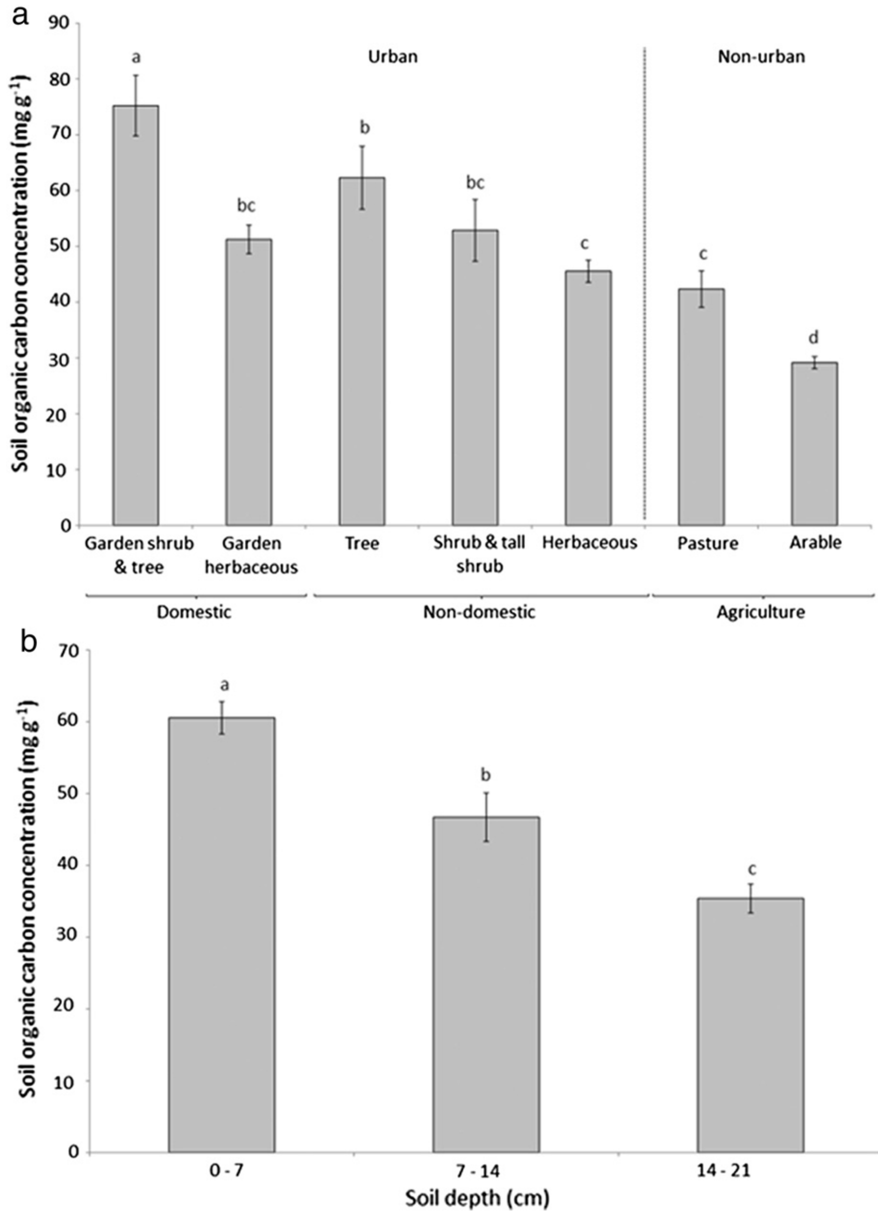

Fig. 2. Mean soil organic carbon concentration (mg g^{-1}) in a) the different greenspace and agricultural land-cover classes and b) in the three soil depth categories. Error bars indicate ± 1 SE. Different letters indicate significant differences in SOC concentration between land-cover classes or soil depth (Tukey test $p < 0.05$).

the soils under trees growing in non-domestic urban greenspace (Fig. 3a). Total median SOC storage density was lowest in arable land, at 7.1 kg m^{-2} to 21 cm, a value almost half that found under shrubs and trees in domestic gardens (Fig. 3a).

3.2. Effect of soil type and soil depth (0–21 cm) on urban topsoil OC concentration and density

Urban topsoil OC concentration (mg g^{-1}) and density (mg cm^{-3}) to 21 cm were not significantly affected by soil types as digitally mapped by Cranfield University (SOC concentration: $F_{(6,\ 228)} = 2.1$, $p = 0.07$; SOC density: $H_{(6,\ 210)} = 10.4$, $p = 0.07$). Both urban SOC concentration (mg g^{-1}) and density (mg cm^{-3}) declined significantly with soil depth (SOC concentration: $F_{(2,\ 228)} = 16.2$, $p < 0.001$; SOC density: $H_{(6,\ 210)} = 26.3$, $p < 0.001$), and there was no interaction between soil type and soil depth (SOC concentration: $F_{(12,\ 228)} = 0.6$, $p = 0.80$; SOC density: $H_{(12,\ 210)} = 6.4$, $p = 0.79$).

3.3. Spatial distribution and budget of greenspace SOC across the city

Citywide topsoil OC storage was calculated by greenspace type and soil depth based on the samples taken in 7 cm sections to 21 cm depth (Table 2). Total SOC storage to 21 cm depth was 411,553 tonnes (95% C.I. = 394,087–492,020) (Table 2). This gives a mean topsoil OC value of 9.9 kg OC m^{-2} within urban greenspace, or 5.6 kg OC m^{-2} of topsoil across the whole city. The garden shrub and tree category in areal extent covers only 11% (Table 1) but the underlying soil contributes 16% of the topsoil OC storage (Table 2). In contrast, the non-domestic herbaceous vegetation provided 46% of total greenspace (Table 1), but contained only 40% of the topsoil OC (Table 2).

The SOC density in greenspaces, to 21 cm depth, varied from between <0.1 to 9.5 kg m^{-2} per 250 × 250 m grid square (6.25 ha) (Fig. 4a). Across the city the suburbs, in which there are both non-domestic greenspace areas and housing areas with relatively large gardens, often with some tree cover, contained the grid squares with the highest SOC stocks in topsoil. As expected, the grid squares

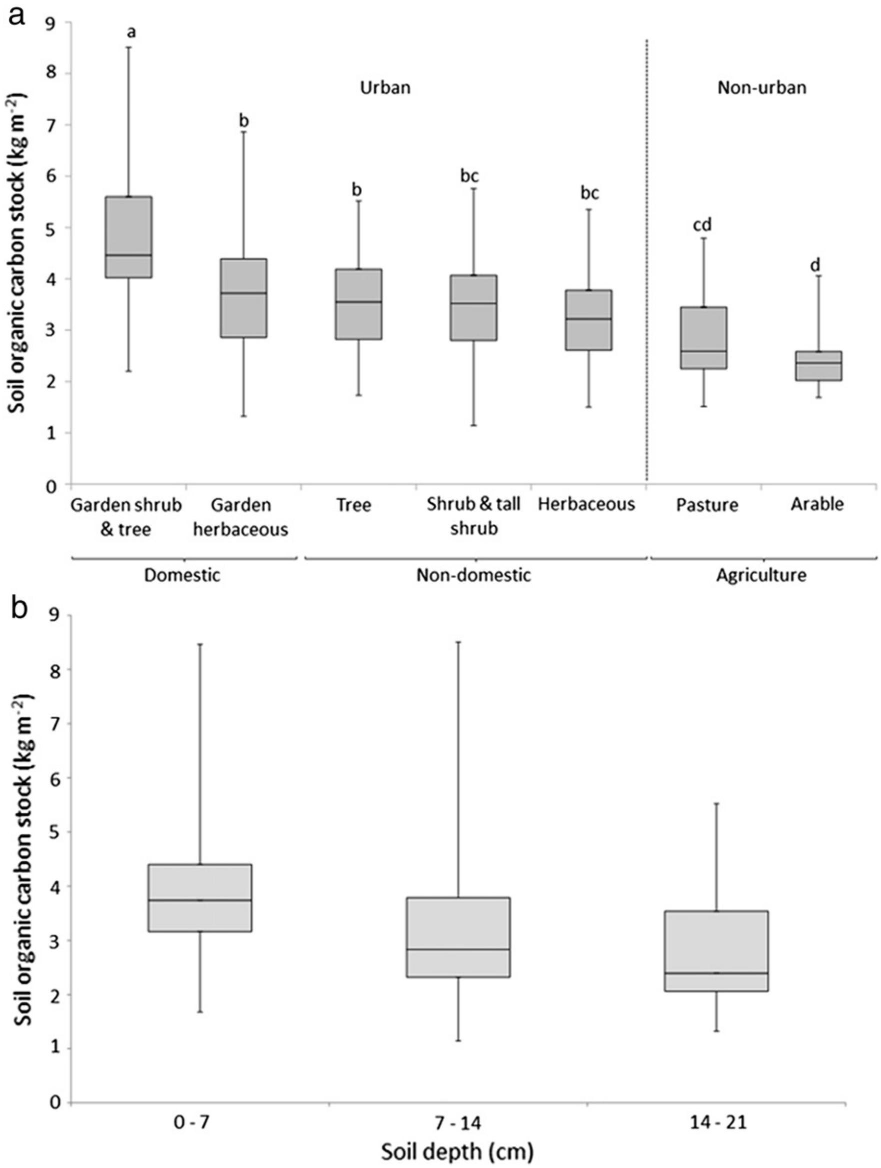

Fig. 3. Median soil organic carbon stocks (kg m^{-2}) in a) the different greenspace and agricultural land-cover classes and b) in the three soil depth categories. Error bars indicate 25th and 75th quartiles. Different letters indicate significant differences in total SOC storage between land-cover classes (Dunn's test $p < 0.05$).

in the city centre tended to hold the lowest SOC storage, reflecting the low proportion and small patch size of greenspace in this part of the city. A frequency histogram of SOC storage, comparing the 50 grid squares centred on the city centre commercial and business district, with the remaining 1005 whole grid squares, revealed that over half the squares containing less than 50 tonnes SOC per grid square (equivalent to 0.8 kg m^{-2}), and nearly a third of those containing only 50–100 tonnes per grid square (or 0.8–1.6 kg m^{-2}) greenspace were located in the city centre (Fig. 4b). However, even within the city centre there were individual grid squares that contained between 300–350 and 350–400 tonnes SOC per grid square (4.8–5.6 kg m^{-2} and 5.6–6.4 kg m^{-2} respectively) in greenspace topsoil. The distribution

Table 2
The quantities of soil organic carbon (SOC) (tonnes) stored across Leicester within each land-cover class and at each depth, measured to 21 cm[a].

	Domestic gardens		Non-domestic greenspace			All greenspace
Soil depth	Shrub and tree	Herbaceous	Tree	Shrub and tall shrub	Herbaceous	Total
0–7 cm	24,307	32,800	25,015	11,049	71,949	165,120
	(21,833–26,781)	(30,014–35,585)	(23,722–26,307)	(9534–12,564)	(66,621–77,278)	(158,319–171,920)
7.1–14 cm	22,817	32,392	18,082	9260	50,653	133,203
	(19,121–26,512)	(27,670–37,115)	(16,345–19,819)	(6248–12,272)	(46,149–55,156)	(124,937–141,470)
14.1–21 cm	19,029	22,168	20,212	9992	41,830	113,230
	(15,406–22,652)	(15,514–28.821)	(10,374–30,050)	(5698–14,286)	(37,600–46,060)	(99,428–127,033)
Total to 21 cm	66,153	87,359	63,308	30,301	164,432	411,553
Contribution to	(60,417–71,888)	(78,738–95,981)	(53,235–73,382)	(24,841–35,761)	(156,273–172,592)	(394,087–492,020)
total SOC storage	16%	21%	15%	7%	40%	

[a] Values in parenthesis are 95% confidence intervals.

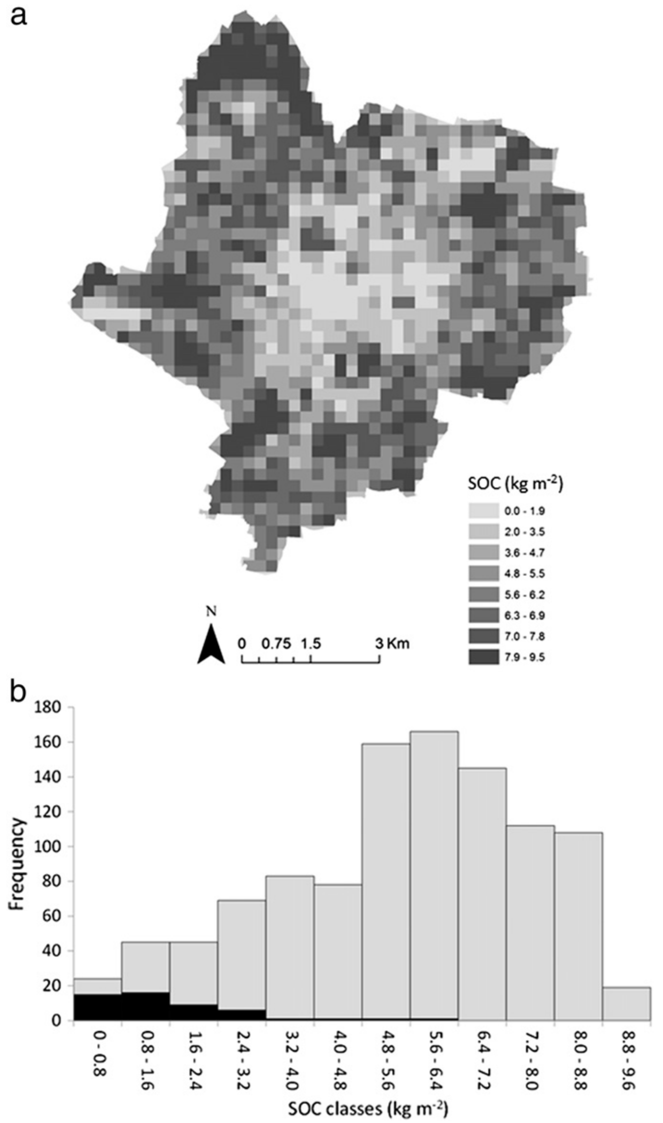

Fig. 4. a) Distribution of soil organic carbon (SOC) to a depth of 21 cm across Leicester in 250 × 250 m grid squares, and b) The frequency distribution of SOC storage (kg m^{-2}) to 21 cm depth in 250 × 250 m grid squares across the city of Leicester, showing the 50 grid squares centred on the commercial and business district (shaded black) and the remaining 1005 grid squares (shaded grey).

of SOC storage in greenspace was positively skewed, with most of the grid squares in the 300–350 and 350–400 tonnes SOC per grid square. The upper limit of SOC storage within individual grid squares occurred where the area of that square was almost exclusively greenspace, often with high tree cover.

4. Discussion

4.1. Topsoil OC density: domestic gardens, non-domestic greenspace and agricultural land

Across the city of Leicester topsoil SOC storage density and concentrations were greater in gardens than in non-domestic greenspace. This is a likely consequence of garden management practices that include additions of organic matter such as peat, composts organic fertilisers and mulches, and the contribution of woody trees and shrubs that tend to enhance SOC stocks as reported previously (Bradley et al., 2005; Osmond and Hardy, 2004; Robbins and Birkinholtz, 2003) and seen in our data. Mulch applications have been shown to add a mean value of 1.5 kg C m^{-2} to gardens in Chicago (Jo and McPherson, 1995), and in the U.K., bark mulches have become popular for weed control, and composts are often added to increase garden fertility or as 'spent' compost from pot plants, management practices that were reported in a survey of households in Leicester (Gaston et al., 2013). The trend of greater SOC storage density in garden soils than non-domestic greenspace has previously been observed in three U.K. cities (Rawlins et al., 2008), as well as in Baltimore, U.S.A. (Pouyat et al., 2009, 2006). These findings contrast to the storage pattern of OC in aboveground vegetation, which was considerably lower in domestic gardens in our study city than in non-domestic greenspaces (Davies et al., 2011), largely due to the greater importance of tree cover in urban parks and small woodlands.

No significant difference was observed in SOC storage to 21 cm between the tree and shrub and tall shrub land-cover classes in the non-domestic greenspace of Leicester, however, they were significantly lower than in the garden shrub and tree land-cover class. SOC storage density within these urban tree and shrub and tall shrub dominated land-cover classes in Leicester was generally higher than previous reports from the U.S.A. and Japan (e.g. Pouyat et al., 2009, 2002; Takahashi et al., 2008; Groffman et al., 2006), although data are not directly comparable due to variation in sampling depths. However, they were consistent with previous estimates for U.K. woodlands, for example 7 kg m^{-2} to a depth of 15 cm (Ostle et al., 2009) and 13 kg m^{-2} to 30 cm (Bradley et al., 2005).

SOC storage density under herbaceous vegetation in non-domestic greenspace did not differ significantly from soil beneath either the shrub and tall shrub, tree and garden herbaceous land-cover classes. Rawlins et al. (2008) reported a mean SOC concentration of 47 mg g^{-1} (approximately 7.1 kg m^{-2}, assuming a soil bulk density of 1 g cm^{-3}), to 15 cm depth, in grassland soils from three U.K. cities, a figure commensurate with the data for Leicester. These data were also within the range reported for urban areas in the U.S.A. (Pouyat et al., 2009, 2006, 2002; Kaye et al., 2008, 2005; Smetak et al., 2007; Jo and McPherson, 1995) although as sampling depths varied between these studies the data are not directly comparable.

The differences in SOC storage density resulted in a proportionally greater contribution to total greenspace stocks from domestic gardens, which provided only 32% of total greenspace area but held 37% of the SOC storage in topsoil. This was driven by the greater levels of storage in the domestic shrub and tree land-cover class. However, urban greenspace tree and shrub land-cover classes, in non-domestic greenspaces did not have significantly greater SOC storage densities than herbaceous vegetation, they covered 22% of the total greenspace and contributed 22% of total SOC storage. These data suggest that topsoil beneath trees and shrubs in urban non-domestic greenspaces do not accumulate SOC to a greater extent than soils beneath herbaceous dominated vegetation, in contrast to the pattern commonly seen in non-urban ecosystems (Bell et al., 2011). It is unclear whether the similar storage concentrations found in all greenspace land-covers (with the exception of the domestic tree and shrub class) were due to specific urban management treatment interactions with the different land-cover types.

Soils in urban greenspace sampled to 21 cm depth were between 21 and 89% higher in SOC content than the adjacent agricultural grasslands (Fig. 3a), not 50% lower as previously assumed (Bradley et al., 2005). SOC storage to 21 cm depth in pasture (8.6 kg m^{-2}) and arable fields (7.3 kg m^{-2}) around Leicester was similar to the mean values for England of 7 kg m^{-2} for arable and 8 kg m^{-2} for pasture to 30 cm depth (Bradley et al., 2005). Importantly, the significantly lower SOC concentrations in agricultural pasture and arable fields than in the urban greenspaces is a reminder of the extent to which agriculture, especially ploughing, use of inorganic fertilisers and crop removal has degraded SOC stocks and soil quality (Lal, 2009, 2008; Bellamy et al., 2005). Agriculture in the East Midlands is predominantly arable, furthermore some of the pasture may form part of an agricultural rotation system and be ploughed and used for arable cultivation. In contrast, although some urban soils are highly disturbed and altered by anthropogenic activities (Lorenz and Lal, 2009), most of the soil in urban greenspaces (such as lawns, woodlands and gardens) is rarely disturbed and so retains SOC, for example, herbaceous vegetation across the city covered 67% of all the greenspace, which in an urban area is a predominantly permanent lawn or grassland. Furthermore, these soils were significantly less compacted than that in the surrounding agricultural region and although the urban soils did have bulk density values that showed a wider range than agricultural soils, none exceeded the limits for plant root growth (Edmondson et al., 2011), providing further evidence that these soils are not functionally compromised.

4.2. Citywide SOC storage, and management implications

The application of high spatial resolution GIS enabled the contributions of small patches of greenspaces even in the dense urban centre to be measured and summed across the city revealing that, at the scale of 250 × 250 m, none of the grid squares was completely devoid of greenspace and consequently SOC. In contrast, U.K. national soil inventories have been based on at a 1 km^2 scale grid, in which areas of 'continuous urban fabric' have been ascribed an SOC value of zero, reflecting in part the resolution CORINE land-cover map (Xu et al., 2011; Bradley et al., 2005; Cruikshank et al., 1998), and widely held assumptions that urban soils are organic carbon depleted. A combination of both the resolution of land-use/land-cover data and lack of measurement of SOC concentrations in urban soils has resulted in the large discrepancy between measured urban SOC stocks (Edmondson et al., 2012) and the assumed urban SOC stocks in the national inventory (see Bradley et al., 2005).

Given the importance of maintaining accurate national soil organic carbon inventories our findings indicate the urgent need to extend the studies we report here to a countrywide analysis of urban SOC stocks for a larger sample of representative cities. This should be targeted to better understand the effect of urbanisation pattern (dense versus sprawling cities), soil type, climate and land management at a national and international level may result in as these factors are all likely to impact on SOC storage. Notwithstanding these constraints our data can be used to indicate the potential importance of urban SOC stocks nationally. For example, in the current national inventory 3.6% of the 1015 Tg SOC to 30 cm depth in English soils is reported to be held in 'suburban land' based on an average storage of 4 kg m^{-2} (Bradley et al., 2005). Using the 9.9 kg m^{-2} greenspace average in Leicester to 21 cm depth, the estimate for storage in 'suburban land' could increase by 53 Tg increasing national storage by 5%. However, this does not include carbon storage in soils in 'urban areas' as defined by the relatively low spatial resolution CORINE land cover maps. Unfortunately, Bradley et al. (2005) do not provide data on the area of England that is counted as 'urban' and assumed by them to contain no SOC. However, it is clear from our spatial analysis that there is an additional quantity of organic carbon in greenspace soils in inner-city areas, that has will not have been accounted for in the national inventory, suggesting a further disparity exists between the current estimates and actual contribution of urban areas additional to that for 'suburban' land.

There is a positive association between SOC concentration and provision of other regulating and supporting ecosystem services provided by soils, particularly in the topsoil which is the vital interface between above- and belowground processes (Franzluebbers, 2002). These critically important services include, water filtration, erosion control, soil strength and stability, nutrient conservation, and pollutant immobilisation (Lal, 2010; Franzluebbers, 2002; Watts et al., 2001; Merrington and Alloway, 1997; Watts and Dexter, 1997). The measurement of high levels of SOC storage in the topsoils sampled in urban greenspaces under different land-covers, in combination with the map of SOC storage distribution across the city demonstrates the extent to which other these other key ecosystem services have been undervalued and overlooked across urban areas. Even within the city centre there were still patches of greenspace with functional soils that should be able to support these multiple ecosystem services.

The research presented within this paper contributes to a rapidly expanding body of quantitative evidence that has challenged the conventional view of urban environments as largely lacking in ecological value (see e.g. Haines-Young, 2009). Such evidence is increasingly demonstrating the provision of multifunctional ecosystem services in urban greenspaces, often above the levels now found in modern agricultural landscapes (Fuller et al., 2009). Urban greenspaces, concurrent with enhancing OC storage in soils and vegetation (Edmondson et al., 2012; Davies et al., 2011), underpin a range of valuable services, including vegetation, regulation of the urban heat island effect (Hart and Sailor, 2009; Gaffin et al., 2008), urban drainage (Whitford et al., 2001), trapping of pollutants (including particulates) with consequent benefits to human respiratory health (Guo et al., 2009; Brunekreef and Holgate, 2002), habitat for wildlife (Gaston et al., 2005) and improved human wellbeing (Fuller et al., 2007; Chiesura, 2004). The importance of SOC as a vital component of the benefits and services provided by greenspaces in dense urban areas demands recognition in land-use policies and planning rules that should seek globally to protect and manage this valuable resource.

To date, there are no examples of urban greenspace management specifically for SOC storage, however urban tree planting has become an extremely popular and increasingly widely implemented strategy to increase urban ecosystem service provision including aboveground carbon storage (Davies et al., 2011). Our previous research has demonstrated that tree planting within non-domestic greenspace can significantly enhance OC stocks aboveground as in our study city urban trees in non-domestic greenspace held 97% of aboveground OC (Davies et al., 2011). However, the present study reveals that tree planting in these areas will not translate into a tangible increase in topsoil SOC storage.

When considering ecosystem OC stocks in cities and towns, a key focus should be the protection of the current resource along with potential enhancement of SOC storage. Provision of this ecosystem service can be directly managed by local authorities as large patches of greenspaces are council owned (for example in Leicester 13% of the city area is council managed greenspace (Davies et al., 2011)); or indirectly managed through planning policy, for example in the U.K. the requirement for planning permission to cover front gardens with impermeable surface could prevent the loss of surface SOC. However, in order effectively to manage the global urban SOC resource there is a clear need to augment the current data to produce well informed management strategies.

Our data reveal that urban greenspaces are already providing a much larger SOC resource than has previously been recognised and necessitates parallel studies in other urban areas to determine its global importance. Although the global extent of urban land is between 2 and 3% of total land mass (MEA, 2005), urban areas are expanding in extent faster than any other land use type (Hansen et al., 2005; McKinney, 2002; Antrop, 2000; Meyer and Turner, 1992) and some countries are more intensely urbanised particularly in Western Europe, for example 14% of the U.K. land is urban (DEFRA, 2005). In addition, cities and towns across the globe cover a range of densities, for example those in the USA tend to be much more sprawling than in Europe (Gaston, 2010), and the regional responses of SOC storage to urbanisation will vary with land-use, land-cover and climate. However, the effects of urbanisation on national or international SOC stocks will depend largely on the nature of the land-use change. For example, whilst our work demonstrates that urban expansion onto degraded agricultural may have a net positive effect on SOC storage, growth into a natural or semi-natural habitat such as moorland may result in a decline in stocks.

An increased understanding is clearly required not only of urban SOC stocks but also the rates of SOC turnover in urban soils, and their response to shifts in urban land-cover, management and environmental change. However, the hypothesised links between SOC storage, land-cover and soil type were not apparent in our case study city, suggesting that processes driving both storage and turnover are controlled by different factors in cities and towns compared to the wider countryside.

Conflict of interest

The authors do not have any personal, financial, or other conflicts of interest with other people or organisations within the last three years that could inappropriately influence, or be perceived to influence, the submitted manuscript.

Acknowledgements

We are grateful to Leicester City Council (most notably D. Bell and D. Mee) for a GIS layer delineating all land parcels that they manage across the city and permission to conduct the soil sampling, as well as the many private and institutional landowners who granted us access to their properties. This work was supported by EPSRC grant EP/F007604/1 to the 4M consortium: Measurement, Modelling, Mapping and Management: an Evidence Based Methodology for Understanding and Shrinking the Urban Carbon Footprint. The consortium has five U.K. partners: Loughborough University, De Montfort University, Newcastle University, University of Sheffield and University of Exeter. Infoterra kindly provided access to LandBase, and MasterMap data were supplied by Ordnance Survey. The BGS digital data were provided under licence 2009/058 from the British Geological Survey, ©NERC. The soil type data within Leicester were provided by Soils Data© Cranfield University (NSRI) and for the Controller of HMSO 2012. Finally, we thank N. McHugh for constructive discussions and Jonathan Potter for technical assistance.

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