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An assessment of urban horticultural soil quality in the United Kingdom and its contribution to carbon storage

Abstract

As participation in urban horticulture grows, understanding the quality of urban horticultural soils is of increasing importance. Until now, case studies of individual cities or gardens have limited the potential of such studies to draw generalised conclusions. Here, we present the first national scale assessment of soil quality in allotments, a dominant form of urban horticulture in the United Kingdom. We sampled soils in 200 allotments in 10 urban areas across Great Britain. We assessed a range of soil quality indicators (carbon and nitrogen concentration, C:N ratio, bulk density, carbon density, pH) comparing them to the quality of soils in rural arable and horticultural land. We present the first estimate of nationwide carbon storage on allotments. We found that allotment gardeners consistently employ management practices conducive to high soil quality. Allotment soil quality differed significantly between soil types but in general soils were of a high quality: low bulk density (0.92 g cm^{-3}) and high soil organic carbon concentration and density (58.2 mg g^{-1} and 58.1 mg cm^{-3} respectively). Allotment soil organic carbon concentration was 250% higher than in the surrounding arable and horticultural land. Covering only 0.0006% of Great Britain, allotments contribute a disproportionate 0.05-0.14% of nationwide total organic carbon stocks. This national-scale study provides compelling evidence that small-scale urban horticultural production, unlike conventional horticulture, does not degrade soil quality. Indeed, allotments hold a small but previously unaccounted for carbon stock nationally. Urban horticultural land is a vital part of the urban landscape with effectively functioning soils that should be protected. As public demand for urban horticultural land rises and policy-makers from local to trans-national

levels of governance advocate for urban food production, our findings demonstrate that urban horticulture can protect or enhance the ecosystem services provided by soils in cities and towns where the majority of people live.

Keywords

Allotments; Carbon storage; Soil organic carbon; Soil quality; Urban agriculture; Urban horticulture

1. Introduction

A growing global urban population has brought with it increasing concern about issues of urban sustainability and food security. Recent research attention has turned to possibilities presented by urban horticulture (UH) to contribute to meeting the nutritional demands of urban residents, predicted to comprise over two-thirds of the global population by 2050 (United Nations, 2019). Urban horticulture is increasingly viewed by international organisations as a facet of ensuring future food security (Mbow et al., 2018), and studies have demonstrated that it has the potential to provide at least 15%, and up to 122%, of a city's residents with fruit and vegetables if all available land was cultivated (Edmondson et al., 2020a; Mcdougall et al., 2020), or thirty days of provision for a city's residents at current levels of cultivation (Grafius et al., 2020).

In addition to providing fruit and vegetables to urban residents, UH is important for ecosystem service provision (Speak et al., 2015; Church et al., 2015; Goldstein et al., 2016; Benis & Ferao, 2017). This includes services supported by UH soils, such as food production (Beniston & Lal, 2012); regulation of climate and floods (Rawlins et al., 2013); storage of organic carbon (Bretzel et al., 2018); nutrient cycling (Lorenz, 2015); and biodiversity support (Tresch et al., 2018). Soils are the foundation for many ecosystem services, but

47 globally face challenges from degradation, land-use change and climate change (Wiskerke &
48 Viljoen, 2012; Eingenbrod & Gruda, 2015). Traditionally, it was assumed that urban soils on
49 the whole are of poor quality, storing limited or no soil organic carbon (SOC) (Pouyat et al.,
50 2006). However, this has been challenged by research demonstrating that they contain
51 internationally significant stocks of SOC, and that not all urban soils are sealed or degraded
52 to the point of being inconsequential in SOC estimates (Pouyat et al., 2006; Edmondson et
53 al., 2012; Edmondson et al., 2014b). In addition, urban greenspace soils contribute to runoff
54 and flood control, mitigate the urban heat island effect, support biodiversity, and improve air
55 quality (Morel et al., 2015; Mbow et al., 2018). SOC is a good indicator of soil quality, being
56 positively associated with water and nutrient holding capacity, and negatively associated with
57 soil compaction (Franzluebbers, 2002; Edmondson et al., 2014b). It is also positively
58 associated with crop yields and ecosystem service delivery (Lal, 2010; Powlson et al., 2011).
59 Globally, soil degradation and land-use change have released ~78 Gt SOC into the
60 atmosphere, and changes in SOC concentration are a major contributor to greenhouse gas
61 emissions (Lal, 2004; Emmett et al., 2010; Batjes, 2014). However, national SOC inventories
62 do not, typically, account for urban SOC stocks (Bradley et al., 2005; de Brogniez et al.,
63 2015).

64 Previous research has found that good soil management is key for the improvement of UH
65 soils to increase yields as well as maximise ecosystem service provision (for example:
66 Lorenz, 2015; Eigenbrod & Gruda, 2015, Tresch et al., 2018). Research addressing the
67 influence of management on urban horticultural soil quality is still relatively young (Lorenz,
68 2018; Tresch et al., 2018); however, practical guidelines for gardeners exist in many forms,
69 for example having been produced by the European Cooperation in Science and Technology
70 framework (COST, 2019), as overall understanding of how to sustainably manage
71 agricultural soils is a mature and comprehensive body of literature. Many common practices

such as composting and manure addition contribute to improving UH soils (Edmondson et al., 2014a). However, urban soils are particularly heterogeneous with a large degree of spatial variability (Lal, 2018), and different underlying soil types can have significantly different properties (Wilson et al., 2011). Case studies in individual cities, which form the bulk of previous research into UH soil quality, whilst presenting some common findings, need corroborating with a nationwide understanding. For example, there is now a body of international literature assessing UH soil quality and the influence of management on UH soil: for example in Pisa, Italy (Bretzel et al., 2018); California, USA (Egerer et al., 2018); Zurich, Switzerland (Tresch et al., 2018); Cotonou, Benin (Brock and Foeken, 2006); and Buenos Aires (González et al., 2010). However, to date no nationwide surveys have been undertaken.

In the UK, allotment gardening is the predominant land-use devoted to UH (Crouch & Ward, 1997; Acton, 2015). Allotment plots are rented land parcels for the purpose of food production, usually around 250 m^2, and form part of larger sites comprised of a varying number of plots. Current UK provision of allotment plots does not meet demand: there are approximately 330,000 allotment plots, covering 135 km^2, however, there were 100,000 people on waiting lists in the last decade (Campbell & Campbell, 2013), and demand for plots is rising (Dobson et al., 2020) particularly in response to the Covid-19 pandemic (Smithers, 2020). Previous research on allotment soils in Leicester, UK, found they had a 32% higher SOC concentration than in regional arable soils (Edmondson et al., 2014a), suggesting that UH occurs without the degradation of soils seen in conventional agricultural systems.

In this paper, we establish the first assessment of soil quality on allotment gardens throughout the Great Britain. As well as investigating SOC density and SOC concentration, which as detailed above is one of the primary indicators of overall soil health (Franzluebbers, 2002),

we also look at other soil quality indicators associated with the provision of regulating and supporting ecosystem services in the soil (Dominati et al., 2010). These are bulk density (BD), a key measure of soil compaction (Emmett et al., 2010); soil total nitrogen (N) concentration and the carbon to nitrogen (C:N) ratio (an important control of soil nutrient cycling; Powlson et al., 2011); pH; and water holding capacity (WHC). Additionally, we use a questionnaire study with plotholders to determine soil management practices and investigate whether these have a significant influence on soil quality. For each of our study cities, we investigate SOC concentration in comparison to their surrounding arable and horticultural rural land, allowing us to compare the quality of UH soils to overall arable and horticultural soil quality in the UK. Further to this, we produce the first estimate of the contribution of allotment soils to British SOC stocks.

2. Methods

2.1.Site selection

We selected ten case study urban areas, geographically distributed across Great Britain: Bristol (B), Cardiff (CA), Edinburgh (ED), Leeds (LD), Leicester (LE), Liverpool (LV), Milton Keynes (MK), Newcastle (NE), Nottingham (NO) and Southampton (SO) (Figure 1). This north-south gradient captured a range of climatic conditions, with average annual rainfall varying from 620 mm to 991 mm, and average annual temperature varying from 8.5 °C to 10.6 °C (Climate-Data.org, 2021; Table 1).

Table 1. Climatic conditions of study cities.

City	Avg. annual rainfall (mm)	Avg. annual temperature (°C)
Bristol	819	9.8
Cardiff	991	10.3
Edinburgh	706	8.5
Leeds	697	9.5
Leicester	620	9.7
Liverpool	796	9.4
Milton Keynes	631	9.6
Newcastle	655	8.5
Nottingham	648	9.8
Southampton	774	10.6

Each urban area was split into four quadrants with an allotment site selected for field sampling randomly from each quadrant in a Geographic Information System (ArcGIS 10.4.1.; Supplementary Information S1 for sites), to give four study sites per city. Within each allotment site five allotment plots were selected for soil sampling. Soils were sampled in 200 allotment plots in 40 sites over the 2017-2018 growing seasons. In addition, for each plot, a map was produced detailing all features present, e.g. cropped areas, grass, impermeable surface, greenhouses.

Figure 1. Location of study cities within Great Britain: Edinburgh (ED), Newcastle (NE), Leeds (LD), Liverpool (LV), Nottingham (NO), Leicester (LE), Milton Keynes (MK), Cardiff (CA), Bristol (B), and Southampton (SO).

Whilst urban areas are spatially heterogenous in regard to soil properties, we were able to identify the general soil type of each site using the NatMap Vector "soilscapes" dataset (National Soil Resources Institute, 2001). Edinburgh sites had no available soil type data. Allotment sites in the remaining nine urban areas existed on ten different soil types: freely draining floodplain soils (FDFS), freely draining lime rich loamy soils (FSLLS), freely draining slightly acid loamy soils (FSALS), freely draining slightly acid sandy soils (FDSASS), lime rich loamy and clayey soils with impeded drainage (LLCSID), loamy and clayey floodplain soils with naturally high groundwater (LCFNHG), loamy and clayey soils

140 of coastal flats with naturally high groundwater (LCCNHG), slightly acid loamy and clayey
141 soils with impeded drainage (SALCSID), slowly permeable seasonally wet acid loamy and
142 clayey soils (SPSWALC), and slowly permeable seasonally wet slightly acid but base rich
143 loamy and clayey soils (SPSWABLC; Figure 2).

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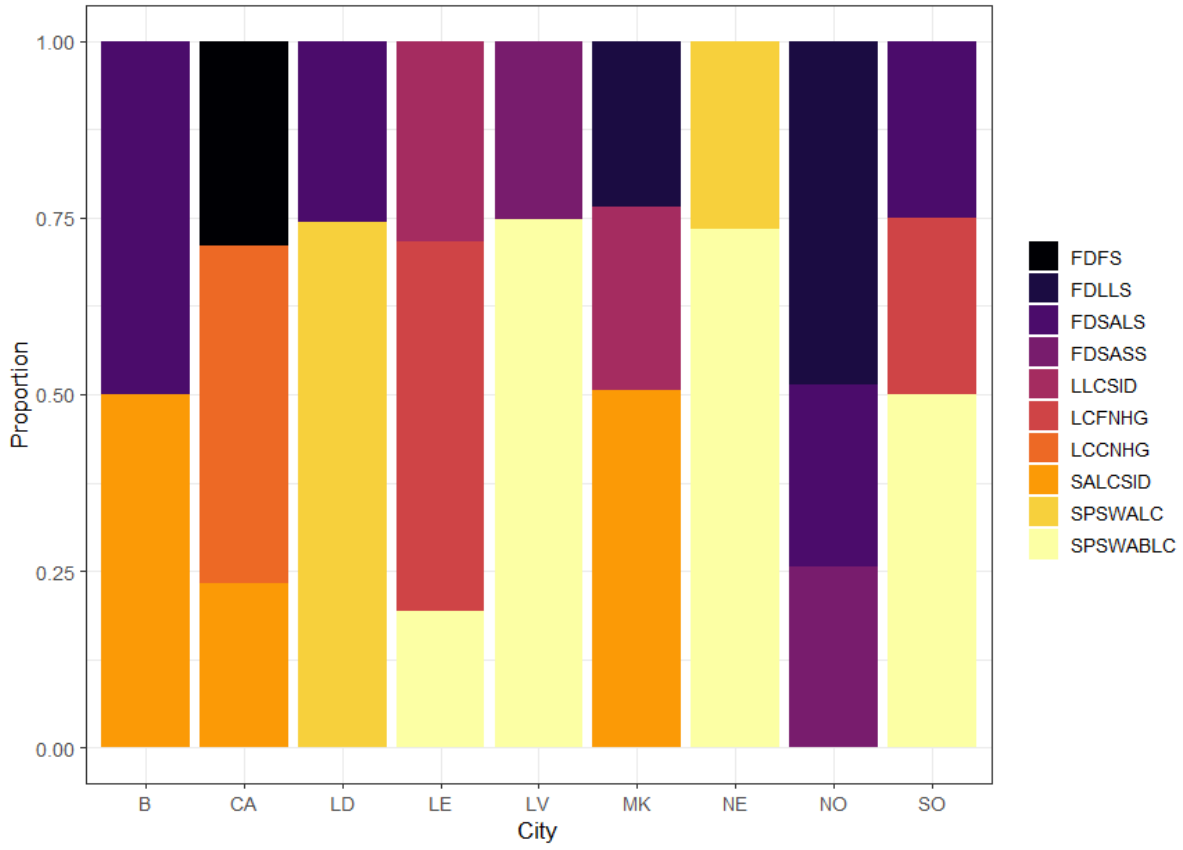

145

146 **Figure 2.** Distribution of soil types on allotments in case study urban areas (n = 20 per urban area): Bristol (B),
147 Cardiff (CA), Leeds (LD), Leicester (LE), Liverpool (LV), Milton Keynes (MK), Newcastle (NE), Nottingham
148 (NO) and Southampton (SO).

149

150 ## 2.2.Soil sampling methods

151 At each allotment plot (n = 200), soil was sampled under one perennial and one annual crop
152 due to the undisturbed nature of soils beneath perennial crops as opposed to beneath annual

crops where crop rotation occurs, in order to assess whether soil properties differed based on this. In plots where there were only annuals or perennials then soils were sampled beneath two different annual or perennial crops. Soils were sampled using two methods. Firstly, at two depth increments (0-10 cm and 10-20 cm) using a specialist bulk density corer (Eijkelkamp Ring Kit C; Edmondson et al., 2012). Secondly, triplicate auger samples were taken to 20 cm depth.

2.3.Soil analysis

Soil samples were dried at 105°C for 24 hours, weighed, ball-milled to homogenise and passed through a 1mm sieve (Edmondson et al., 2012). Material >1mm was weighed and removed from soil total weight; this material was then volumetrically measured using water displacement and the volume removed from total volume to calculate soil BD (g cm^{-3}). Inorganic carbon was removed from samples with 5M HCl, and the remaining soil was analysed for SOC and N in an elemental analyser (Vario EL Cube; Isoprime, Germany). SOC density (mg cm^{-3}) was calculated individual samples using SOC concentration (mg g^{-1}) and BD prior to the removal of the volume of >1mm material (g cm^{-3}) (Edmondson et al., 2012).

Auger samples were air dried and analysed for water holding capacity (WHC) and pH. Soil pH was determined in 1:10 (v:w) ratio with 0.01 M $CaCl_2$ suspension (Houba et al., 2000). Prior to WHC analysis, auger samples were passed through a 9 mm sieve. The “European” maximum water holding capacity method of Gardner (1986) was used to determine WHC based on the weight of water held by soil as a percentage of the dry weight of the soil.

175 **2.4.Soil management questionnaire**

176 Questionnaires were conducted with 184 of the 200 allotment plotholders on whose plots soil
177 samples were taken. Participants were asked a variety of questions related to plot and soil
178 management practices, such as organic growing, manure use, winter coverings, and
179 composting of plot waste (Supplementary Information S3).

180

181 **2.5.Agricultural soil carbon concentration**

182 LandCover Map 2015 (Rowland et al., 2017) was used to identify areas of arable and
183 horticultural land surrounding each urban area. Ten locations were selected at random (in
184 ArcGIS 10.4.1; for Cardiff and Liverpool, only nine were available) within this agricultural
185 land surrounding each urban area. At each location (n = 88) a topsoil organic carbon value
186 was extracted from NatMap Vector (National Soils Resources Institute 2001). Comparison
187 was conducted on this geographic basis rather than by soil type in order to compare soil
188 quality between places that had similar climatic conditions; however, soil type was
189 comparable within and without study cities, and all arable and horticultural locations selected
190 matched the underlying soil texture of their closest allotments according to the NatMap
191 Vector data. This was not possible in Edinburgh as NatMap Vector does not extend into
192 Scotland.

193

194 **2.6.Allotment contribution to nationwide SOC stocks**

195 For each soil type sampled, we converted the median SOC density (mg cm^{-3}) for 0-10 cm and
196 10-20 cm to give SOC storage (kg m^{-2}) to 20 cm. We used the Ordnance Survey Greenspace
197 map (Ordnance Survey, 2007) to identify all allotment sites in Great Britain and combined

198 this with the NatMap Vector dataset to identify the soil type for each allotment site. For all
199 allotments in Scotland (where no soil type data was available), and for allotment sites on soil
200 types unrepresented in the allotment soil survey, we applied a minimum, maximum and mid-
201 range estimate for SOC storage to 20 cm in kg m^{-2} based on our minimum, maximum and
202 median measurements for SOC in national-scale allotment survey.

203 To prevent over-estimation of SOC we accounted for land area within allotment sites that is
204 not used for cultivation. Communal infrastructure that can seal soil covers 18% of allotment
205 sites and so was assumed to hold no SOC (Edmondson et al., 2020b). Average area of land
206 used on an allotment plot for impermeable surface area, horticultural production soil, or other
207 permeable surfaces such as grass paths were calculated using plot maps. Average
208 impermeable area per plot was also removed from each allotment site.

209 We used the Land Cover Map 2015 GB Vector (Rowland et al., 2017) alongside the NatMap
210 Vector soil type data and NatMap Vector carbon map to deduce the soil type and SOC value
211 of each arable and horticultural land parcel. NatMap Vector SOC, estimated to 30cm, was
212 converted to an estimate to 20cm to align with our field values. For Scottish land parcels,
213 which did not have NatMap Vector coverage, we applied an overall median of SOC storage
214 estimation. For each allotment land parcel across the country, estimates for the potential
215 minimum, maximum and mid-range SOC storage were calculated twice: firstly, on the
216 assumption that all permeable surface on allotments maintains equal SOC values to the
217 cropped areas; secondly, on the assumption that all permeable surface on allotments that is
218 uncropped has SOC storage equal to rural arable and horticultural land rather than allotment
219 crop area. This gave us two possible estimates for SOC storage overall on allotments.

220

2.7.Statistical analysis

Statistical analysis was conducted in R version 4.0.0. (R Core Team, 2020; see Supplementary Information S4 for a full list of R packages used). The mean of the two replicated samples was taken for each allotment plot, to give one result per plot depth per crop type (annual or perennial), except for pH and WHC, where only one depth was sampled.

We examined the influence of soil type, crop type and depth (for pH and WHC, depth was excluded) on our measured soil quality indicators. Data were transformed where necessary to improve the fit to assumptions of normality at $p \geq 0.05$ using Shapiro-Wilk tests, and linear mixed effects models were built to include the influence of city or allotment site as random effects using the R package *lme4* (Bates et al., 2015). Using Akaike's information criteria (AIC) values and 95% confidence intervals, the most parsimonious model for each variable was built. The package *lmerTest* (Kuznetsova et al., 2017) was used to generate *p*-values for the models using Satterthwaite's approximation. Linear mixed effects models were also used to investigate the influence of management practices on soil quality. A paired sample t-test was used to analyse differences between allotment and arable and horticultural SOC concentration.

3. Results

3.1. Allotment soil management

Plotholders had managed their plots for a median length of 7 years, ranging from two weeks, to 61 years. Previous growing experience prior to taking on their allotment ranged from none to a lifetime of growing, but the majority (76%) had no experience of growing food before

taking up their plot. When a plotholder's previous experience was added to the length of their plot occupancy, plotholder median food growing experience increased to 11 years.

Forty-three percent of respondents self-reported growing organically, 43% grew mostly organically, and 13% were non-organic. Fifty-four percent of questionnaire respondents used winter covering on their beds, most commonly black plastic, Geotex membrane and green manure. The most common soil additions were garden waste compost (92%) and manure (82%) with addition of other material less common (Table 2).

Table 2. Inputs to allotment plots by survey respondents.

Additions to plot	**Yes %**	**No %**
Home kitchen waste compost	67	33
Compost from allotment organic matter waste	92	8
Purchased compost	69	31
Other compost*	33	67
Manure	82	18
Fertiliser (organic)	38	62
Fertiliser (non-organic)	27	73

* For example: cardboard, livestock straw, ash.

3.2. Allotment soil quality

Overall, the median properties of allotment soils were BD of 0.92 g cm^{-3} (0.22-1.52 g cm^{-3} range); SOC density of 58.1 mg cm^{-3} (16.7-191.8 mg cm^{-3} range); SOC concentration of 58.2 mg g^{-1} (14.0 to 305.6 mg g^{-1} range); N concentration of 3.7 mg g^{-1} (0.75-7.95 mg g^{-1} range); C:N ratio of 16.0 (7.0-40.0 range); pH of 6.5 (4.8 to 7.2 range), and WHC of 71.8% (44.6 to 105.7% range). Most soil properties varied by urban area (Figure 3). The greatest SOC density, SOC concentration, C:N ratios and WHC were found in Cardiff; Leicester had the lowest SOC density and WHC. Milton Keynes had the lowest SOC concentration and C:N ratio, and the highest BD. pH was lowest in Edinburgh (Figure 3).

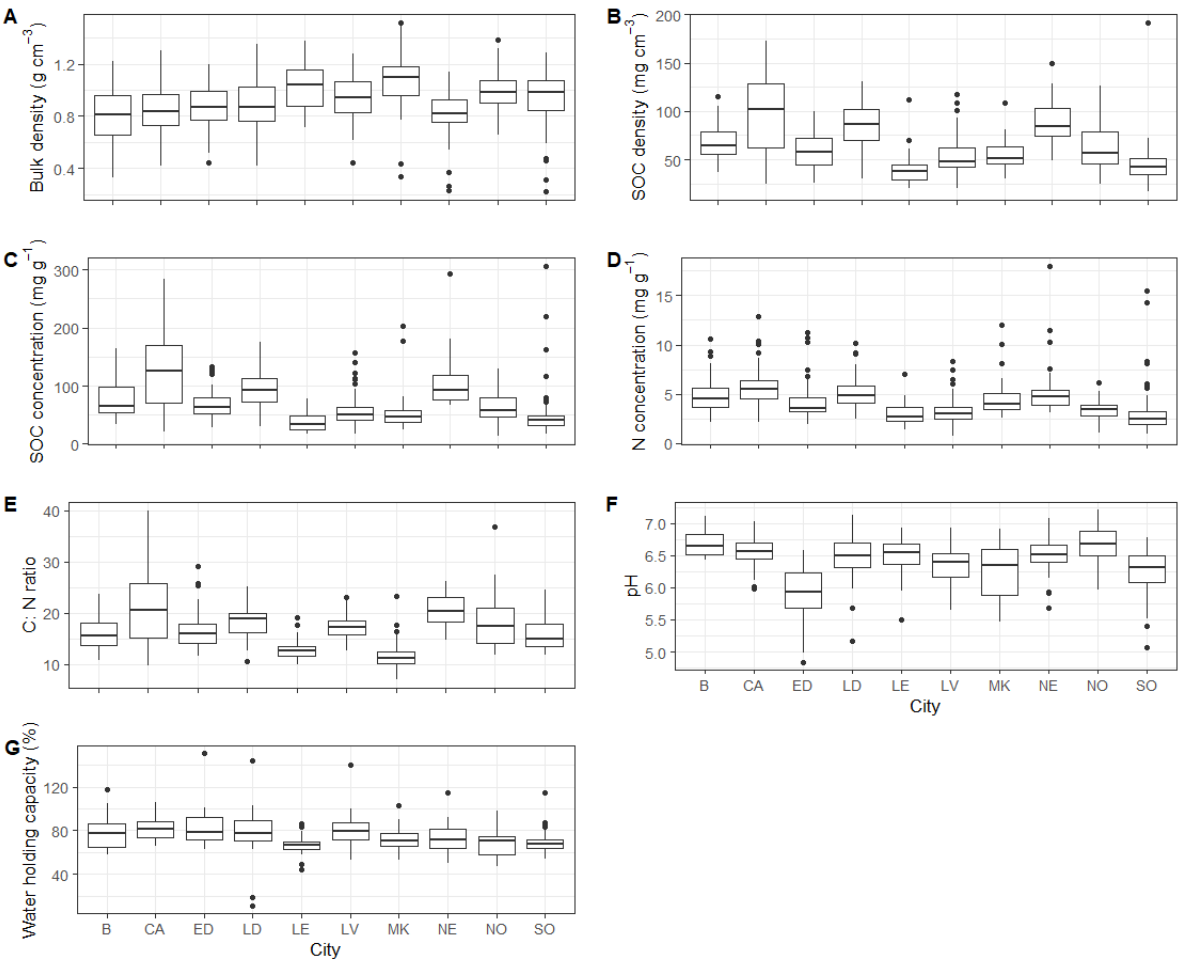

Figure 3. Graphs showing medians, interquartile ranges and outliers for soil quality indicators on allotments sampled in ten British urban areas: Bristol (B), Cardiff (CA), Edinburgh (ED), Leeds (LD), Leicester (LE),

Liverpool (LV), Milton Keynes (MK), Newcastle (NE), Nottingham (NO) and Southampton (SO). **A**: Bulk density, **B**: SOC density; **C:** OC concentration; **D:** N concentration; **E**: C:N ratio; **F:** pH; and **G:** water holding capacity.

For all soil properties measured the most parsimonious models included depth (where applicable), crop type, and soil type, except for N concentration where no fixed effects were included (Table 3). Soil type significantly affected SOC density (df = 9, 566.4, F = 2.1, p = 0.027), C:N ratio (df = 9, 603.7, F = 2.0, p = 0.034), and WHC (df = 9, 184.8, F = 5.4, p < 0.0001) (Figure 4). There was a significant interaction effect between crop type and soil type on pH (df = 9, 92.5, F = 2.7, p = 0.005). Depth did not influence any soil property. Soil type was the most important factor effecting soil properties (Figure 4; Table 3). When plot management practices were included, there was no improvement in model performance, suggesting that there were no significant effects of management on soil quality (Supplementary Information S5).

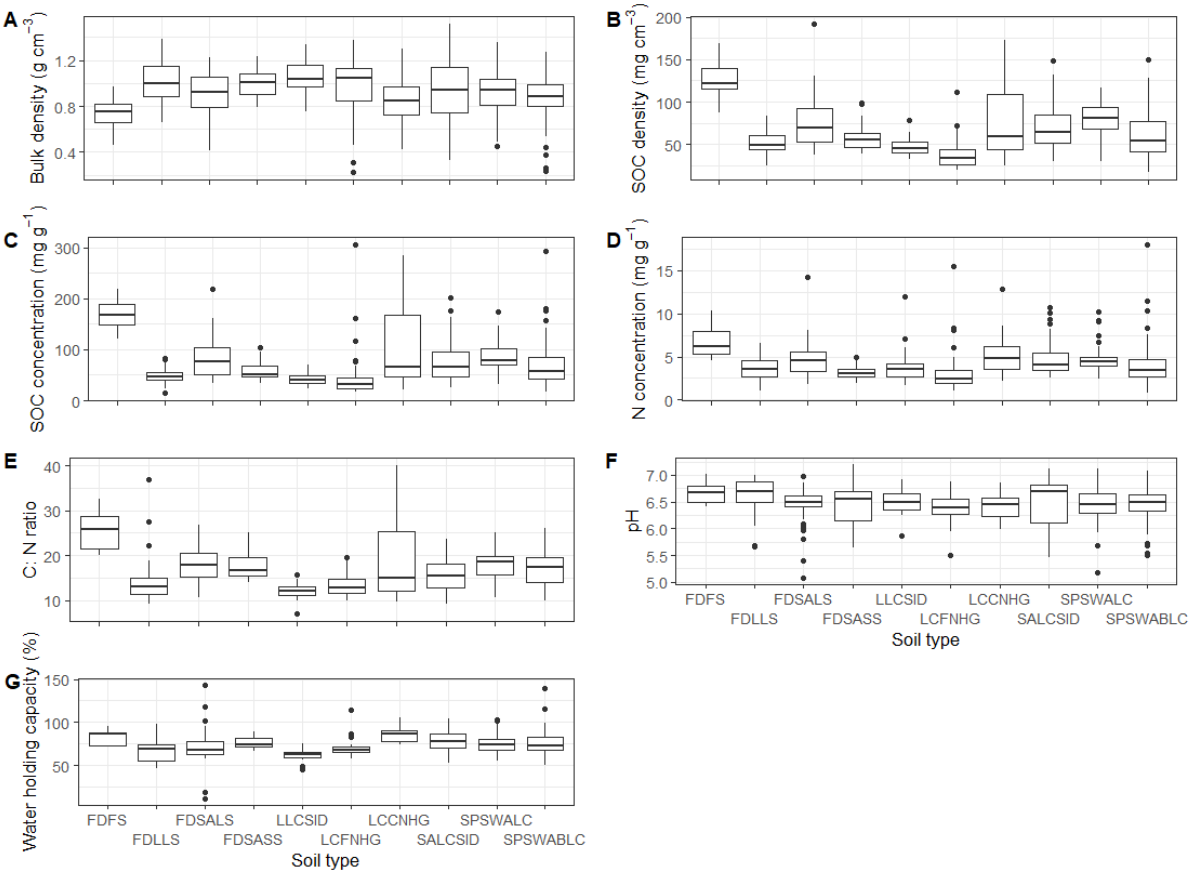

Figure 4. Graphs showing medians, interquartile ranges and outliers for soil quality indicators on allotments according to soil type: **A**: Bulk density, **B**: SOC density; **C:** OC concentration; **D:** N concentration; **E**: C:N ratio; **F:** pH; and **G:** water holding capacity. Soil types abbreviated as follows: freely draining floodplain soils (FDFS), freely draining lime rich loamy soils (FSLLS), freely draining slightly acid loamy soils (FSALS), freely draining slightly acid sandy soils (FDSASS), lime rich loamy and clayey soils with impeded drainage (LLCSID), loamy and clayey floodplain soils with naturally high groundwater (LCFNHG), loamy and clayey soils of coastal flats with naturally high groundwater (LCCNHG), slightly acid loamy and clayey soils with impeded drainage (SALCSID), slowly permeable seasonally wet acid loamy and clayey soils (SPSWALC), and slowly permeable seasonally wet slightly acid but base rich loamy and clayey soils (SPSWABLC).

Table 3. Soil quality indicators on allotments analysed using linear mixed effects models, showing transformations applied to the data; the model terms (fixed and random effects) included that created the most parsimonious model for each variable; the results of type III analysis of variance on each of the fixed terms in

each model. For N concentration, no analysis was performed as the model was most parsimonious without any fixed effects.

Variable	Transformation	Fixed effects	Random effects	Results	Annual / perennial	Depth category	Soil type	Crop type : depth	Crop type : soil type	Depth : soil type	Crop type : depth : soil type
Bulk density	None	Crop type, depth, soil type	City	F	$_{1,595.8}$ = 0.55	$_{1,596.0}$ = 0.93	$_{9,601.4}$ = 1.80	$_{1,595.78}$ = 0.09	$_{9,595.81}$ = 0.55	$_{9,595.96}$ = 0.74	$_{9,595.82}$ = 0.41
				p	0.81	0.34	0.07	0.76	0.83	0.67	0.93
SOC density	Log	Crop type, depth, soil type	City	F	$_{1,560.88}$ = 1.52	$_{1,560.95}$ = 0.47	$_{9,566.37}$ = 2.11	$_{1,560.89}$ = 1.78	$_{9,560.89}$ = 0.50	$_{9,560.98}$ = 0.54	$_{9,560.91}$ = 0.39
				p	0.22	0.49	**0.03**	0.18	0.87	0.85	0.94
SOC concentration	Log	Crop type, depth, soil type	Site	F	$_{1,598.91}$ = 0.02	$_{1,598.93}$ = 2.13	$_{9,604.71}$ = 0.86	$_{1,598.9}$ = 0.21	$_{9,598.92}$ = 0.43	$_{9,598.95}$ = 0.43	$_{9,598.91}$ = 0.26
				p	0.90	0.14	0.56	0.65	0.92	0.99	0.98
N concentration	Square-root	None	City & site	F	-	-	-	-	-	-	-
				p	-	-	-	-	-	-	-
C : N	Log	Crop type, depth, soil type	City	F	$_{1,598.98}$ = 0.43	$_{1,598.98}$ = 0.00	$_{9,603.72}$ = 2.03	$_{1,598.96}$ = 0.12	$_{9,598.97}$ = 0.48	$_{9,598.99}$ = 0.16	$_{9,598.97}$ = 0.26
				p	0.51	0.99	**0.03**	0.72	0.89	0.99	0.98
pH	Exponential	Crop type, soil type	City & site	F	$_{1,293.05}$ = 3.17	-	$_{9,22.50}$ = 0.96	-	$_{9,292.49}$ = 2.67	-	-
				p	0.07	-	0.50	-	**0.005**	-	-
Water holding capacity	Log	Crop type, soil type	City	F	$_{1,295.46}$ = 0.65	-	$_{9,184.82}$ =5.39	-	$_{7,295.64}$ = 0.20	-	-

297

3.3. Organic carbon in allotment soils compared to arable and horticultural soils

Median SOC concentration in arable and horticultural soils was 23.5 mg g^{-1}, compared to 58.15 mg g^{-1} for allotment soils across Great Britain. Allotment SOC concentration was significantly higher than that of arable or horticultural soil from the surrounding region ($t = 7.80$, $df = 8$, $p < 0.0001$, Figure 5).

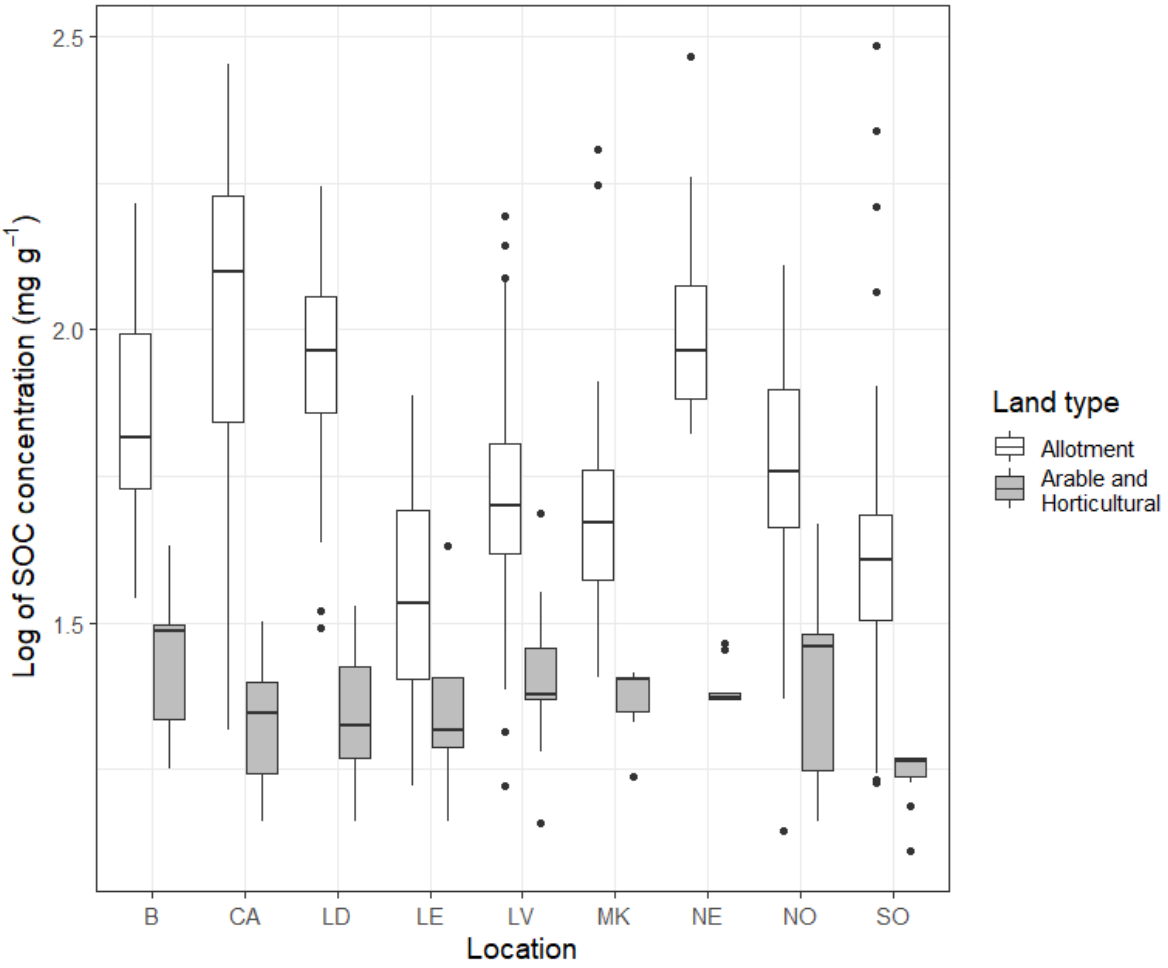

Figure 5. Graph showing medians, interquartile ranges and outliers for soil organic carbon concentration in topsoil (0-20cm) in allotments within cities, and arable and horticultural land surrounding each urban area: Bristol (B), Cardiff (CA), Leeds (LD), Leicester (LE), Liverpool (LV), Milton Keynes (MK), Newcastle (NE), Nottingham (NO), and Southampton (SO).

3.4. Soil organic carbon storage contribution of British allotments

National median SOC storage to 20 cm depth in land cultivated for food production in allotments was 11.5 kg m^{-2}. Highest SOC storage (24.4 kg m^{-2} 20 cm depth) occurred in loamy and clayey floodplain soils with naturally high groundwater and in freely draining floodplain soils storage was estimated to be lowest (6.7 kg m^{-2} 20 cm depth; Figure 6). See Supplementary Information S6 for estimates of SOC storage for all British allotment sites identified by Ordnance Survey. Our field mapping found that 14.4% ±2.7% of allotment plots are impermeable surface; 31.9% ±2.1% is uncultivated permeable surface such as grass paths, and 53.4% ±1.5% is cultivated (crops and ornamental planting).

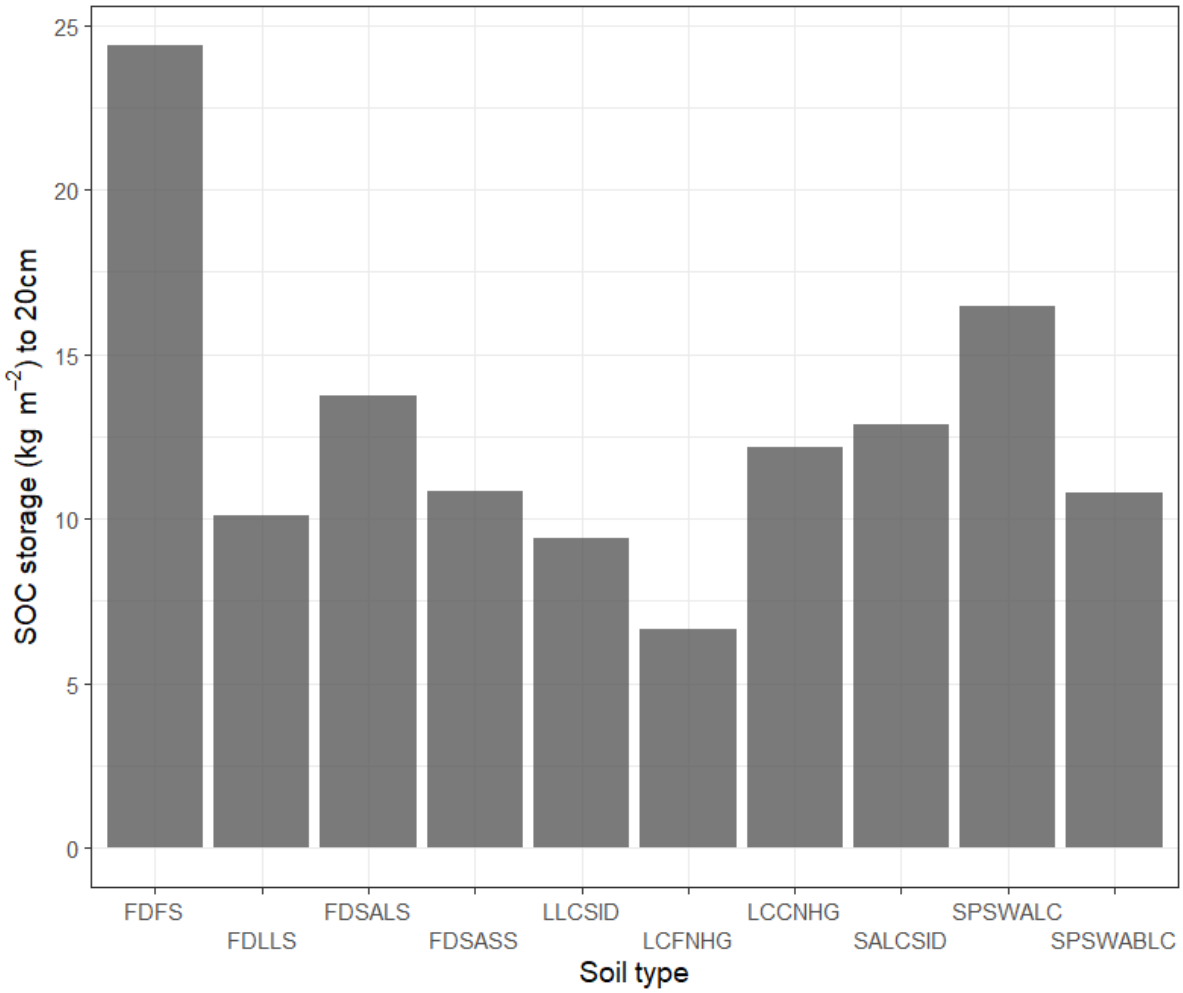

Figure 6. Soil organic carbon storage (kg m^{-2}) to 20 cm depth by soil types on allotments: freely draining floodplain soils (FDFS), freely draining lime rich loamy soils (FSLLS), freely draining slightly acid loamy soils (FSALS), freely draining slightly acid sandy soils (FDSASS), lime rich loamy and clayey soils with impeded drainage (LLCSID), loamy and clayey floodplain soils with naturally high groundwater (LCFNHG), loamy and clayey soils of coastal flats with naturally high groundwater (LCCNHG), slightly acid loamy and clayey soils with impeded drainage (SALCSID), slowly permeable seasonally wet acid loamy and clayey soils (SPSWALC), and slowly permeable seasonally wet slightly acid but base rich loamy and clayey soils (SPSWABLC).

We estimate allotment SOC storage (Tg to 20 cm) in Great Britain ranges from 1.35-2.15 Tg if permeable surfaces on allotments maintain the same SOC levels as cultivated areas, and 0.86-1.37 Tg if permeable uncultivated areas have an SOC storage level the same as rural arable and horticultural land (Table 4).

Table 4. Estimates of carbon storage on British allotments.

Method	**Minimum SOC storage (Tg to 20cm)**	**Mid-range SOC storage (Tg to 20cm)**	**Maximum SOC storage (Tg to 20cm)**
All allotment permeable areas have the same SOC values	1.35	1.55	2.15
Uncultivated permeable areas have arable land SOC values	0.86	0.99	1.37

335 ## 4. Discussion

336 Previously, site-specificity of research limited our understanding of the nature and properties
337 of UH soils (Borysiak et al., 2016). Whilst, globally, research into the quality of UH soils has
338 been increasing in recent years and is drawing up a positive international picture regarding
339 UH worldwide (Brock and Foeken, 2006; González et al., 2010; Bretzel et al., 2018; Egerer
340 et al., 2018; Tresch et al., 2018), to date no nationwide surveys have been undertaken. Here,
341 using data at a national scale, we can assess overall properties of allotment soils, and compare
342 their SOC concentrations with those of arable and horticultural land. We find that UH soils in
343 allotments maintain levels of SOC across Great Britain that are significantly higher than
344 those found arable and horticultural soil.

345 SOC is one of the most important overall indicators of soil health (Franzluebbers, 2002). The
346 most recent Countryside Survey, a national-scale survey that includes measures of soil health
347 across Great Britain (Emmett et al., 2010), found that average SOC concentration for arable
348 and horticultural land was 30.7 mg g^{-1}. This is higher than the 23.5 mg g^{-1} we found, but still
349 substantially lower than the average allotment SOC concentration of 58.2 mg g^{-1}. Allotment
350 SOC concentrations from our field data were similar to improved grassland, which had an
351 SOC concentration of 56.9 g kg^{-1} (Emmett et al., 2010).

352 Bulk density on allotments was 0.92 g cm^{-3}, compared to 1.23 g cm^{-3} for arable and
353 horticultural soil reported nationally (Emmett et al., 2010). This is lower than the BD
354 reported for allotments in a case-study in Leicester (Edmondson et al, 2014a); however, our
355 values for Leicester were consistent with this study. Bulk density is typically negatively
356 correlated with SOC and provides a proxy measure for soil compaction with higher bulk
357 density values indicating more compacted soils (Edmondson et al., 2011). Compaction has
358 negative impacts for erosion and flood mitigation, as well as impeding plant growth

(Edmondson et al., 2011). We found lower pH on allotments than those reported in the Countryside Survey from arable and horticultural soils (6.5 vs. 7.2; Emmett et al., 2010). For horticultural production, a pH of 6.5 is ideal, allowing optimum earthworm activity and nutrient availability (Royal Horticultural Society, 2020). Total N concentration was higher on allotments than in arable and horticultural soils (3.7 mg g^{-1} vs. 2.5 mg g^{-1}; Emmett et al., 2010), and C:N ratio was also higher (16.0 vs. 11.3; Emmett et al., 2010). The higher C:N ratio is linked to reduced N leaching and maintaining good levels of nutrient cycling, which is also supported by higher WHC (Dominati et al., 2010; Robinson et al., 2013). Overall C:N ratios in this nationwide study were slightly higher than those reported on allotments in Leicester but were consistent with the soils in that urban area (Edmondson et al., 2014a).

Non-urban British soils store an estimated 1582 Tg of OC to 15 cm (Emmett et al., 2010). Our estimates suggest that allotment soils store a further 0.86-2.15 Tg to 20 cm, with the true value likely to be at the higher end of this estimate, given that most urban greenspaces are higher in SOC concentration than rural arable and horticultural land (Edmondson et al., 2014b). Whilst this suggests that allotments only add another 0.05 to 0.14 % to nationwide SOC stock estimates, allotments comprise only 0.0006% land in Great Britain. This suggests that their contribution to SOC stocks is high compared to their areal extent. As only one example form of urban greenspace, this estimation, whilst small, demonstrates the need to accurately assess the total contribution of all forms of urban greenspace to national SOC stocks. It is further evidence that discounting urban greenspace, and specifically urban horticultural land, from estimates in SOC stocks results in underestimation of SOC stocks nationally. As urbanisation is forecast to replace agricultural expansion as the primary driver of land-use change globally, it is increasingly important to accurately estimate urban SOC stocks (Lorenz & Lal, 2015). Further, it is evidence that UH maintains a consistently high level of soil quality, not suffering from the degradation seen in other agricultural land.

384 Overall, management practices undertaken by allotment gardeners mirror those recommended
385 for the maintenance of soil health and organic matter (Lorenz & Lal, 2009; Lorenz, 2015;
386 Gregory et al., 2016). However, some heterogeneity in influence has also been found, for
387 example an excess of N fertilisation on allotments over five years leading to low C:N in
388 allotments in Pisa, Italy (Bretzel et al., 2018); and the finding that sociodemographic factors
389 affect soil quality in community gardens in California, USA, with more affluent communities
390 better able to manage their soil for long term sustainability and soil health (Egerer et al.,
391 2018). However, our analyses did not reveal any consistent findings regarding the influence
392 of soil management techniques on soil quality. There are a number of possible reasons for
393 this result, which goes against established scientific opinion on the ability of soil management
394 to influence soil properties, including in UH contexts (Bell et al., 2016; Bretzel et al., 2018;
395 Egreger et al., 2018; Tresch et al., 2018). Firstly, our questionnaires with plotholders asked
396 them about whole-plot management; the management of the specific crops sampled may have
397 varied. This means that the management practices detailed in the questionnaire responses
398 may not have directly related to the soils which were sampled. Further to this, long-term
399 management of soils has substantial impacts on their qualities (Lorenz, 2015). Previous
400 tenants on the same plot may have managed their soil differently, which would affect those
401 plots where tenancy had only recently been undertaken. Finally, allotment soils were in
402 consistently good health, giving limited scope for variations in management revealed by the
403 questionnaire responses to produce significant variation in the soil quality. This is borne out
404 by the fact that our questionnaire results provided good evidence that UH gardeners manage
405 their soils in ways that are known to be effective in supporting long-term food security and
406 soil health (Tresch et al., 2018; Bretzel et al., 2018), corresponding to good practice
407 guidelines such as those from COST (COST, 2019). Any future expansion of UH should,
408 therefore, follow current practices of food production, utilising knowledge exchange to

ensure that when UH land use expands, sustainable soil management practices continue to be employed, and that sociodemographic factors are taken into account so municipal authorities can target education and resource provision to communities more in need of assistance in maintaining good soil quality (Tresch et al., 2018; Bretzel et al., 2018; Egerer et al., 2018).

We found a consistently significant impact of soil type on soil properties, underscoring the need for nationwide approaches to truly understand the properties of urban soils. In future research, biological indicators would provide a further lens through which to examine urban horticultural soil quality, as demonstrated by Zhang (2019); bacterial community composition is an important indicator of ecosystem health. However, the potential dis-services of allotment soils are also in need of further research. This includes issues such as heavy metal contamination and the bio-availability of soil heavy metals; as well as any potential for NPK accumulation (Lorenz, 2018). Adverse health effects of UH through soil contamination have been contested (Leake et al., 2009; Mees & Stone, 2012), but further research is necessary in this area. Indeed, different management practices have been shown to lead to different levels of heavy metal accumulation in UH soils (Bretzel et al., 2018).One paper has however found that risk perception may be a more limiting factor than risk itself in UH, so continued education of its multiplicity of benefits and potential ecosystem service provision is important (Wortman & Lovell, 2013). Opportunities also exist in future research to investigate the potential for the required inputs (e.g. water) for UH to be sourced from within the urban system, utilising waste energy to improve sustainability (Kumar & Hundal, 2016; Mcdougall et al., 2020). In general, further research directions should focus on continuing to improve our understanding of the factors driving the maintenance of high soil quality levels in UH at national and international scales. Other soil-based UH types could be investigated, perhaps building on the work of Loram et al. (2008) to identify the typical crop area cultivated by

gardeners who grow food in home gardens, and uncover whether allotment UH soil quality is maintained in domestic gardens, which occupy an even greater areal extent than allotments, and present another important area in which to consider SOC storage. Researchers should also investigate possible areas where trade-offs exist between different ecosystem services, leading to an understanding of the best way to practice UH that delivers the maximum benefits for both human wellbeing and ecosystem health. As an expanding body of research on yields in UH (Edmondson et al., 2020a; Mcdougall et al., 2020) feeds into policies for scaling up urban horticultural production, our findings provide promising empirical evidence to demonstrate that such upscaling would also improve other soil-based ecosystem services (such as climate change mitigation, flood mitigation, filtration, and biodiversity conservation; Dominati et al., 2010; Edmondson et al., 2012; Rawlins et al., 2013) alongside food provision.

5. Conclusions

This research has demonstrated that urban horticultural soils are of a consistently high quality, for the first time expanding case study locations to a national scale. Our findings add to the evidence base that UH maintains considerably higher levels of SOC than arable and rural horticultural soils, and performs better on other soil quality indicators as well. We have shown that allotments function as a reservoir of SOC, contributing to the national carbon budget and underscoring the need for thorough assessment of urban soils within this. We have also demonstrated that management practices on allotments follow techniques conducive to sustainable crop productivity as well as ecological health. Overall, our findings suggest a potential for valuable ecosystem service provision by UH soils beyond that of just food production. This further contributes to a growing evidence base of the value of UH.

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6. References

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