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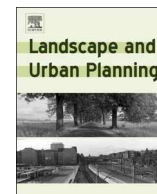
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Research Paper

Contrasting distributions of urban green infrastructure across social and ethno-racial groups

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ABSTRACT

Links between urban green infrastructure (UGI) and public health benefits are becoming well established. Despite this, how UGI is distributed varies widely. Although not a universal finding, sectors of society that are disadvantaged often suffer from poor provision, something which might be due to which UGI are examined. We assess the distribution of street trees and public greenspaces (two types of publicly-owned and accessible UGI) across the city of Bradford, UK which is characterised by high levels of inequality and variation in ethno-racial background. We do this through statistical and spatial analyses. Street tree density was distributed unevenly and was highest in neighbourhoods with a high proportion of Asian/Asian British residents and with lower socio-economic status. Conversely, neighbourhoods with better access to public greenspaces were characterised by high income and/or a high proportion of White households. While the quality of public greenspace was spatially clustered, there were only limited spatial associations with ethno-racial group or socio-economic status. Population density was a key determinant of the distribution of UGI, suggesting understanding UGI distributions should also focus on urban form. Nevertheless, within the same city we show that equitable distribution of UGI differs according to the form and characteristics of UGI. To fully realise the public health benefits of UGI, it is necessary to map provision and understand the causal drivers of unequal distributions. This would facilitate interventions that promote equitable distributions of UGI based on the needs of the target populations.

1. Introduction

Rapid expansion of urban areas and human populations began in the late 20th century and will continue in the coming decades, with around 70% of people estimated to be living in towns and cities by 2050 (United Nations, 2014). Consequently, natural landscapes are becoming less accessible to increasingly urbanized societies. As natural environments have been found to enhance human health and wellbeing (Hartig, Mitchell, de Vries, & Frumkin, 2014), such a reduction in accessibility will have detrimental effects on the quality of life of city dwellers through, for example, a lack of recreational space and increased exposure to pollutants (Lovasi, Quinn, Neckerman, Perzanowski, & Rundle, 2008; Nisbet & Zelenski, 2011).

Urban green infrastructure (UGI; including all green elements such as parks, public greenspaces, green corridors, street trees, urban forests, green roofs and private domestic gardens (Tzoulas et al., 2007)) has emerged as a concept which can help facilitate the inclusion of natural elements within the urban planning process (Sandström, 2002). By

defining, and subsequently valuing, its benefits (Gómez-Baggethun & Barton, 2013), UGI provision can be weighed against competing priorities for city planners, such as housing and infrastructure development (Elmqvist et al., 2015; Groenewegen, van den Berg, Maas, Verheij, & de Vries, 2012; Norton et al., 2015). Providing UGI could, therefore, be an effective way of mitigating the loss of natural environments within cities undergoing processes of densification, and thus enhance human health and wellbeing for a wide cross-section of urbanised societies (Dallimer et al., 2011; Pauleit, Ennos, & Golding, 2005). Numerous studies point to the health benefits of UGI such as improved mental and physical health (Dadvand et al., 2014; Gascon et al., 2016; McEachan et al., 2016; van den Berg et al., 2015, 2016). Although there is considerable evidence for these benefits, knowledge of the pathways that produce them remains limited (Markevych et al., 2017). Reasons may be a combination of mechanisms, including reducing exposure to harmful pollutants, facilitating physical activity and providing stress reducing environments (Hartig et al., 2014). UGI has also been shown to reduce the impact of extreme weather events (Zhang, Xie, Zhang, &

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Fig. 1. The location of Bradford within the United Kingdom (right). Coordinates: 53.7960° N, 1.7594° W. The left-hand panel shows the 218 Lower Layer Super Output Areas (LSOAs) with over 15% of their area covered by built land uses, which were contiguous with the urban core of the city, are shown in grey. Unshaded LSOAs were not included in the study.

Zhang, 2012), boost economic opportunities (Conway, Li, Wolch, Kahle, & Jerrett, 2010) and strengthen community cohesion and reduce crime rates (Kazmierczak, 2013). There is, however, potential for negative outcomes, most notably increased exposure to allergens, to which urban populations can be more susceptible (Cariñanos & Casares-Porcel, 2011), economic and social costs associated with maintenance (Heynen, Perkins, & Roy, 2006) and the possibility of spaces facilitating crime or being perceived as dangerous (Bogar & Beyer, 2016). Nevertheless, recent studies have called for an increase in greenspace provision and inclusion in health promotion policies (Nieuwenhuijsen, Khreis, Triguero-Mas, Gascon, & Davvand, 2017; van den Bosch & Nieuwenhuijsen, 2017).

Aside from private spaces such as domestic gardens and many green roofs, urban green infrastructure is an inclusive element of towns and cities that is freely accessible to all. Therefore, given that some benefits of UGI can be considered public goods (i.e. they are non-rivalrous and non-excludable), UGI, especially when provided and maintained by municipal authorities, could be an effective way of enhancing the liveability of cities for all residents, regardless of socio-demographic background (Hughey et al., 2016; Lee & Maheswaran, 2011). Moreover, research shows a reduction in health inequalities related to income deprivation in mortality rates and circulatory disease, in greener areas, indicating deprived areas have the most to gain from urban greening (Mitchell & Popham, 2008). Despite such potential, UGI tends to be unevenly spatially distributed through urban areas, often resulting in ethnic/racial minorities (Heynen et al., 2006; Landry & Chakraborty, 2009; Wolch, Wilson, & Fehrenbach, 2013) and/or those of lower socio-economic status having comparatively worse provision, or quality of provision, than their counterparts (Vaughan et al., 2013). Numerous methodologically varied studies have shown this phenomenon in terms of accessibility, frequency, size and quality (Boone, Buckley, Grove, & Sister, 2009; Hughey et al., 2016; Schwarz et al., 2015; Tooke, Klinkenber, & Coops, 2010). However, these patterns are not universal; in some cities ethno-racial minorities or those of lower socio-economic status have better provision of UGI (Barbosa et al., 2007; Jones, Brainard, Bateman, & Lovett, 2009; Kessel et al., 2009).

Variation in the patterns of distribution of UGI may, in part, be due to which forms and characteristics of UGI are studied and how equity is assessed. Some studies examine publicly provided UGI, such as street trees (Landry & Chakraborty, 2009; Lovasi et al., 2008) or public parks

(Barbosa et al., 2007; Boone et al., 2009; Comber, Brunson, & Green, 2008; Hughey et al., 2016; Vaughan et al., 2013; Wolch et al., 2013; Zhou & Kim, 2013); others do not distinguish between UGI which is publicly accessible and that which is not, by examining urban tree canopy cover (Heynen et al., 2006; Schwarz et al., 2015; Zhou & Kim, 2013) or the abundance of vegetation/greenness (Li, Zhang, Li, Kuzovkina, & Weiner, 2015; Pham, Apparicio, Séguin, Landry, & Gagnon, 2012; Tooke et al., 2010).

While we might expect uneven distribution of privately owned UGI, as higher income residents can both afford to own larger plots of land allowing for more private greenspace (Pearce, 2003) and often have more social capital, which allows them greater influence over their neighbourhoods (Kendal, Williams, & Williams, 2012; Pham, Apparicio, Landry, Séguin, & Gagnon, 2013; Shanahan, Lin, Gaston, Bush, & Fuller, 2014), publicly owned or maintained UGI should conceivably be subject to a higher level of distributional scrutiny. Indeed, were the health and wellbeing of all residents to be prioritised, we might expect publicly owned UGI to be evenly distributed or even to favour neighbourhoods with little provision of private greenspaces (Boone et al., 2009; Landry & Chakraborty, 2009; Pham et al., 2012).

Current findings are inconsistent in terms of provision and quality for ethnic minorities and lower socio-economic groups. Here, within the multi-ethnic and socioeconomically diverse city of Bradford, UK, we assess the distribution, and quality (an often-overlooked but important factor in assessing equity in UGI; Hughey et al., 2016) of UGI. We answer the research question that certain communities are systematically discriminated against. The environmental equity hypothesis, which states that different demographics and socio-economic groups should be equally impacted by environmental benefits and burdens, provides a framework to assess our question (Cutter, 1995; Downey & Hawkins, 2008; Wen, Zhang, Harris, Holt, & Croft, 2013).

2. Methods

2.1. Study system

Despite cities in the UK often being characterised by a diverse ethnic make-up, deprivation and income levels (Elvers, Gross, & Heinrichs, 2008; Rutt & Gulsrud, 2016) few studies of how UGI is distributed across socio-demographic or ethno-racial groups have thus far been

carried out. Our study is based in the city of Bradford in Northern England (Fig. 1). With a current population of 531,176 (ONS, 2016), Bradford developed rapidly during the industrial revolution. However, since the mid-20th century, much of the original industry has been lost, and in this time the city became a destination for immigrant populations predominantly from South Asian countries such as India, Pakistan and Bangladesh (Hall, 2013). Now well established, these ethno-racial groups account for 19.8% of the population (Bradford Bradford Observatory, 2012). However, in some central areas the proportion of non-White residents rises to 85% (Kelly, 2015; ONS, 2011). In addition to an ethnically diverse population, Bradford is characterised by high levels of income inequality, including neighbourhoods ranking amongst the most and least deprived in the country. As a whole, the city itself is one of the most deprived in the country, with high levels of deprivation centred in ethnic minority communities (Bradford Observatory, 2010). This is typical of the UK where South Asian populations are generally less affluent and more segregated than in other countries, such as Canada and U.S., where similar levels of immigration have occurred (Johnston, Poulsen, & Forrest, 2007).

The municipal authority boundary for Bradford includes both countryside and smaller villages. We therefore concentrated on the urban areas of Bradford (Fig. 1). We defined this as all Lower Layer Super Output Areas (LSOA; the second smallest scale division for which census and other demographic data are available in the UK (ONS, 2014) which had at least 15% of their area covered by built land uses (roads, buildings and other sealed surfaces (OS Street View, 2013); and were contiguous with the central urban core of the City of Bradford itself. This excluded from our analysis both rural areas and smaller satellite towns to the north and west of the city while ensuring the inclusion of LSOAs on Bradford's urban fringe. Of the 310 LSOAs in the municipality of Bradford, we included 218 LSOAs with a total population of 373,794 residents (ONS, 2011) in our analyses.

2.2. Data collection and processing

We carried out our analyses at the LSOA level, which typically include 1000–3000 residents (mean = 1560) (Bates, 2008). This means their spatial extent is variable (mean area = 0.46 km²; Fig. 1). LSOAs represent an appropriate unit of analysis to assess equity in UGI as there is likely to be variation of provision and accessibility of UGI over the study system, and they are sufficiently small to capture this in a dense urban area (Pham et al., 2012; Schwarz et al., 2015; Shanahan et al., 2014). The size of spatial aerial units can be important when examining environmental equity (e.g. Schwarz et al., 2015). However what research there is on methodological issues of this type, suggests that when using UK census data, the choice of aerial unit makes little or no difference to findings (Flowerdew, 2011).

From the 2011 UK census (ONS, 2011) we extracted ethnicity, household deprivation and population statistics for each LSOA (Table 1; Fig. 2). Mean household deprivation was used to represent socio-economic status within an LSOA. It is a multi-dimensional measure, ranging between 0 and 4 for each household based on employment,

Table 1

Socio-demographic and urban green infrastructure (UGI) variables for LSOAs in Bradford, UK.

	Number of LSOAs	Median (to 3 s.f.; interquartile range)
Household Deprivation (0–4)	218	1.11 (0.889–1.36)
White (%)	218	73.9 (34.1–90.6)
Asian/Asian British (%)	218	18.1 (3.85–56.0)
Street tree Density (km ⁻²)	218	129 (65.5–234)
Neighbourhood Greenspace Accessibility (%)	218	61.0 (22.8–83.0)
Greenspace Quality (%)	203	55.5 (52.5–60.6)

education, health, disability and housing (ONS, 2014). Using multiple indicators makes it a more effective measure of socio-economic status than median household income, which is often employed in studies on environmental equity (Galobardes, 2006; Nolan & Whelan, 2010). Although the indicator does not cover all aspects of a household's socio-economic status, it is readily available through the census making it easily and widely applicable. In the UK census data, ethnic categories are reported as percentages for each LSOA. Within Bradford, 85% of the population report as either 'White' (English/Welsh/Scottish/Northern Irish/British, Irish, Gypsy or Irish Traveller, Other White) or 'Asian/Asian British' (Indian, Pakistani, Bangladeshi, Chinese, Other Asian), with the remaining ethnicity categories not well represented (ONS, 2012). To allow for meaningful analysis, we only used the ethno-racial categories of 'White' and 'Asian/Asian British'. As is often the case when forming categorisations for census data these combine ethnic, racial and national characteristics. This part of our analysis is, therefore, comparing two distinctly different, yet amalgamated, ethno-racial groups (Aspinall, 2013; Byrne & Wolch, 2009; Johnston et al., 2007). Finally, we calculated population density (total population/LSOA area), which we used as a proxy for urban density, thus accounting for some aspects of urban form (Mellander, Lobo, Stolarick, & Matheson, 2015).

2.3. Urban green infrastructure

For the purposes of this paper, we use Naumann's et al. (2011) definition for the European Commission of UGI: 'Green infrastructure is the network of natural and semi-natural areas, features and greenspaces in rural and urban, and terrestrial, freshwater, coastal and marine areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and benefit human populations through the maintenance and enhancement of ecosystem services. Green infrastructure can be strengthened through strategic and co-ordinated initiatives that focus on maintaining, restoring, improving and connecting existing areas and features as well as creating new areas and features.' This definition encompasses natural and semi-natural features, and although it emphasises strategic initiatives, this is not a pre-requisite, and therefore it allows the inclusion of remnant greenspaces and vegetation (including trees) which has grown within urban areas without intentionally being planted.

2.4. Street tree density

Street trees are defined as trees on public land beside roads (Landry & Chakraborty, 2009). Publicly owned and managed, street trees represent a highly visible and potentially ubiquitous feature of the urban natural environment. They have been shown to deliver benefits such as reducing asthma rates and improving social cohesion for residents (Lovasi et al., 2008; Mullaney, Lucke, & Trueman, 2015; Peckham, Duinker, & Ordóñez, 2013; Ulmer et al., 2016). Disservices, for instance, blocking pathways and causing damage to property, if they are not adequately maintained, have also been noted (Heynen et al., 2006). The City of Bradford have committed to conserving and maintaining their existing 18,000 street trees and have mapped the location and canopy extent of the entire portfolio. Maps were generated by combining high-resolution aerial photography with highway data. Each tree was assigned co-ordinates and cross-referenced with Google Street View to ensure accuracy, allowing us to calculate street tree density (trees km⁻²) for each LSOA (Fig. 3A).

2.5. Neighbourhood greenspace accessibility

To calculate a measure of greenspace accessibility for each LSOA, we made use of the City of Bradford's public greenspace database (which includes parks and gardens, outdoor sports facilities and amenity greenspaces; (City of Bradford MDC, 2006). In the UK, the Accessible Natural Greenspace Standard (ANGSt) recommends that everyone

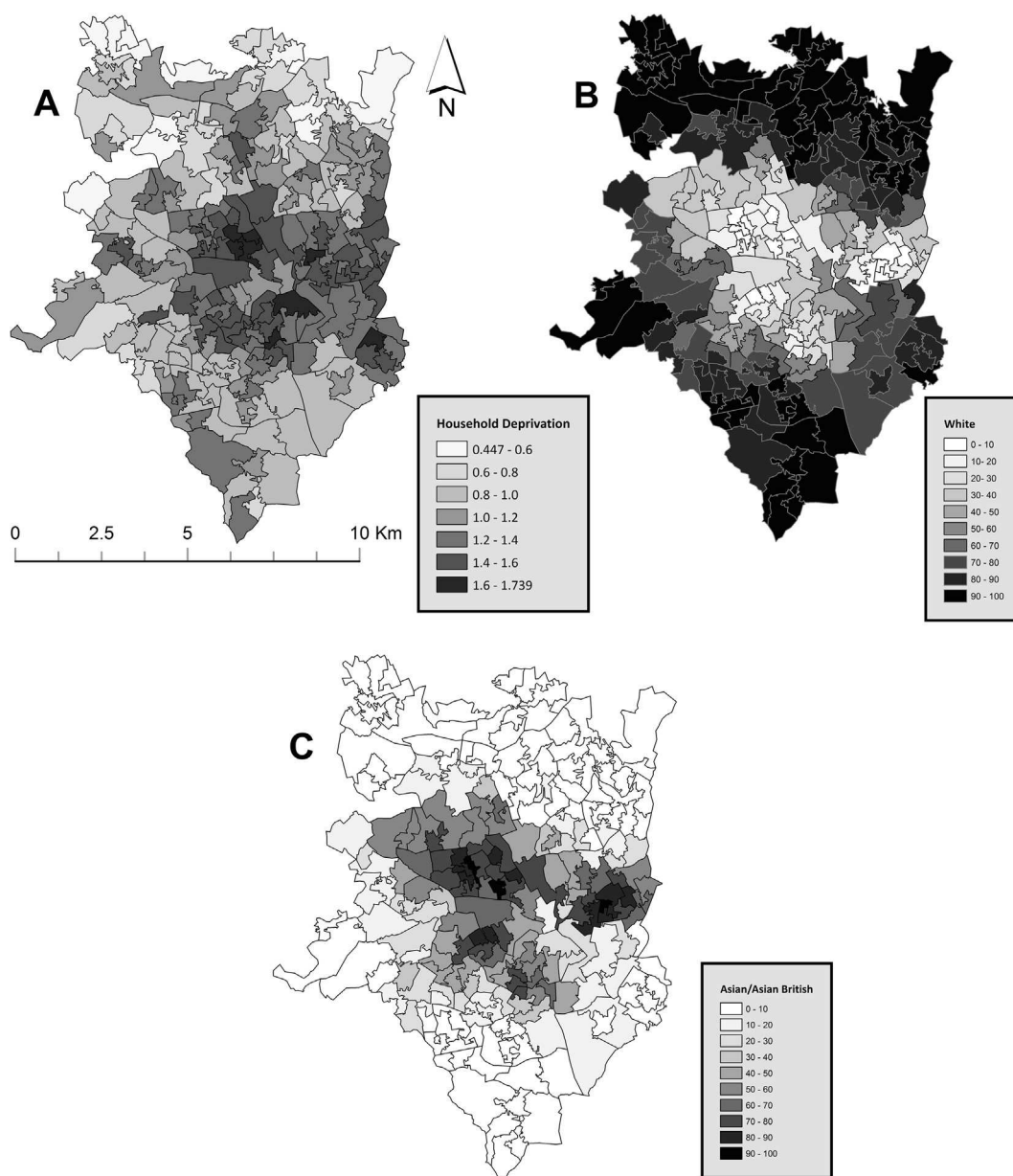


Fig. 2. Spatial variation in socio-demographics across LSOAs within Bradford, UK. (A) Mean household deprivation score; (B) % self-reporting as White; and (C) % self-reporting as Asian/Asian British.

should live within 300 m of greenspace at least 2 ha in size; as this is a distance perceived by potential users to be accessible both to those with disabilities and to children (Natural England, 2010). ANGSt standards recommend that an ‘Equality Impact Assessment’ in line with their guidelines is undertaken to ensure that greenspace provision accommodates all potential users. In line with these national guidelines our measure assesses the Euclidean distance to greenspace. While Euclidian distances have known drawbacks, such as not taking into account barriers to pedestrians or a lack of walking routes (cf. Higgs, Fry, & Langford, 2012), and will not always match residents’ perceptions of accessibility (which can be influenced by the characteristics of the greenspaces themselves, as well as socio-demographic makeup of populations (Jones, Hillsdon, & Coombes, 2009; Maroko, Maantay, Sohler, Grady, & Arno, 2009), it aligns with current policy definitions, and allows accessibility to be quantified across a wide area relatively easily. Further, although the use of network distances (i.e. the distance along transport routes) has become more commonplace, the two measures tend to be highly correlated and any differences between them lessened

in urban areas (Jones, Ashby, Momin, & Naidoo, 2010). In line with the national standards, we excluded greenspaces that were smaller than 2 ha and also those not open to the wider public (e.g. school grounds and golf courses). The ANGSt provides a broad definition of natural environments. We therefore considered open countryside as publicly accessible greenspace (Natural England, 2010) and included countryside (land with human population density of below 1500 people km⁻² ONS, 2013; OS Street View, 2013) within our greenspace categorisation. Based on Euclidean distances we applied a 300 m measurement around our greenspaces and calculated the percentage of each LSOA that had sufficient access to a public greenspace according to national guidelines (Fig. 3B).

2.6. Greenspace quality

Greenspace quality was measured using the Natural Environment Scoring Tool (NEST) (Gidlow et al., 2018), a version of the Neighbourhood Green Space Tool (NGST) (Gidlow, Ellis, & Bostock, 2012)

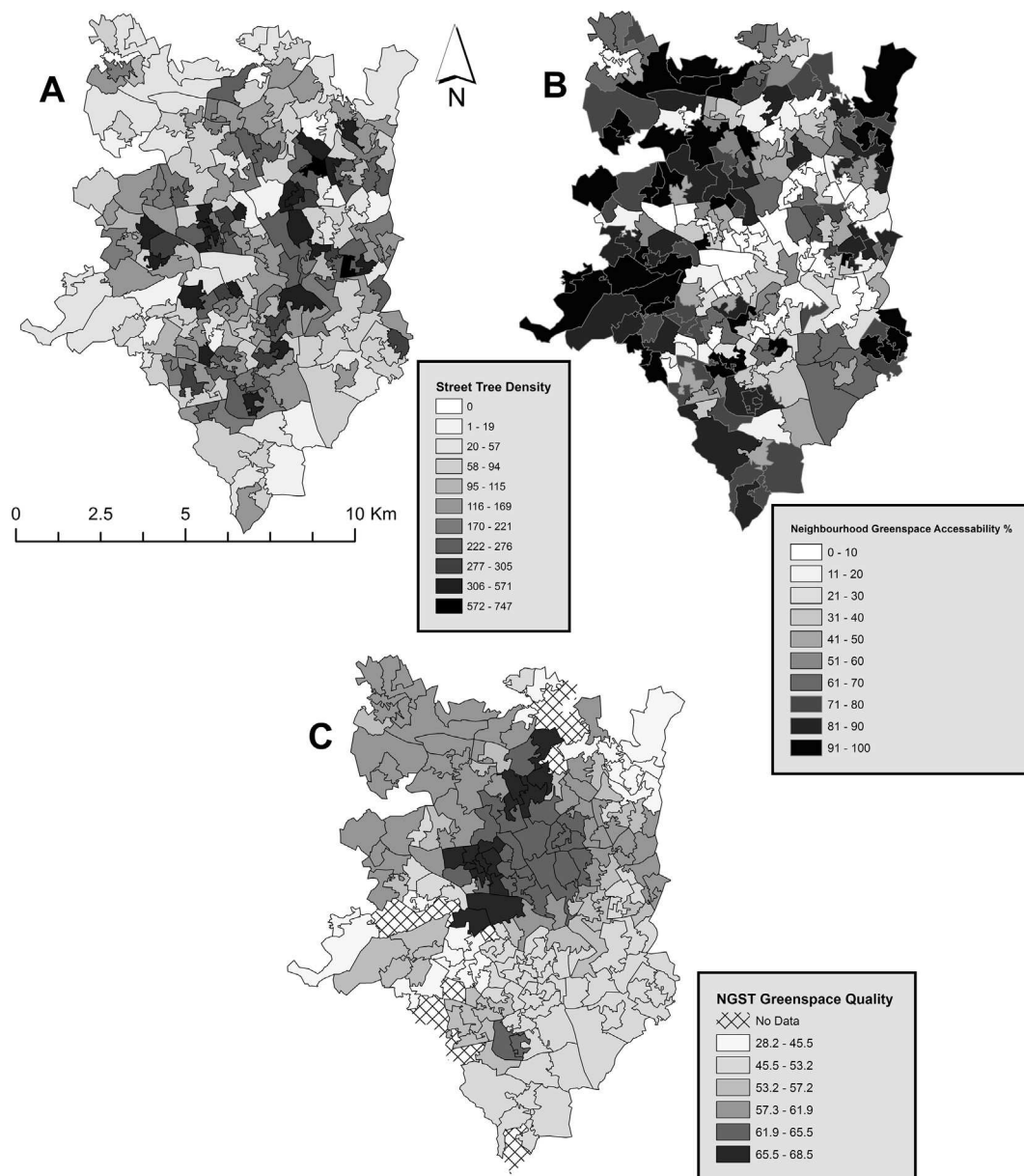


Fig. 3. Spatial variation in the distribution of urban green infrastructure across Bradford, UK. (A) Street tree density (trees km⁻²); (B) accessible neighbourhood greenspace, a measure derived from the Accessible Natural Greenspace Standard (ANGSt); and (C) greenspace quality, which was calculated using the Natural Environment Scoring Tool.

adapted for PHENOTYPE (Nieuwenhuijsen et al., 2014). Observers score each greenspace based on access, recreational facilities, amenities, natural features, non-natural features, incivilities, safety and usage. The NGST itself is a moderately good indicator (i.e. different observers score the same features in the same way) for both individual domains within the Tool (ICC = 0.575–0.948) and overall quality scores (ICC = 0.727, $p < 0.001$) (Gidlow et al., 2012). We included 34 greenspace quality audits in our analyses that fell within our study area (out of 45 in total audited for a separate study (Roberts et al., in review)). Greenspace quality scores, were based on the average score from two independent assessors. The level of agreement calculated between observers was high (ICC = 0.90, $p < 0.001$).

The NEST is applicable to many greenspace typologies so we focused on the most relevant aspects for urban residents. Due to the effect that elements of greenspace can have on the perception of users and, consequently, the benefits it can provide we weighted more strongly the NEST categories that contained more relevant data, when calculating

the overall NEST scores. Levels of neglect (e.g. maintenance/quality and incivilities; Dallimer et al., 2014), perception of safety (Maas et al., 2009), abundance of natural/semi-natural features (Aesthetics – Natural Features; Dallimer et al., 2012; Fuller, Irvine, Devine-Wright, Warren, & Gaston, 2007; Lin, Fuller, Bush, Gaston, & Shanahan, 2014) and accessibility (Access; del Saz Salazar & García Menéndez, 2007) were highlighted as important in this context and were therefore weighted more strongly. We excluded two elements, usability for water sports & fishing, as they were not relevant for the urban greenspaces in our study.

Each LSOA was given a greenspace quality score which was a weighted average based on the relative coverage by the different greenspace's catchment which overlapped with the area of the LSOA (Fig. 3C). ANGSt defines a greenspace's catchment according to its size, with larger parks having a larger catchment, representing how residents typically travel further to utilise them (Natural England, 2010; Schipperijn, Stigsdotter, Randrup, & Troelsen; Rossi, Byrne, &

Pickering, 2015). For the purposes of our study, a greenspace catchment is the buffer applied around each greenspace according to ANGSt guidelines. We assumed that populations within that catchment have their provision of greenspace met. Greenspaces of less than 20 ha provide a 300 m catchment; over 20 ha spaces provide a 2 km catchment and spaces over 100 ha provide a 5 km catchment (Natural England, 2010). Fifteen LSOAs were excluded from this part of the analysis, as they did not fall within any catchments. Due to the variety of possible methods of deriving greenspace quality, sensitivity analysis was undertaken using (i) NEST standard weightings and (ii) increasing catchments to 500 m for greenspaces less than 20 ha. Similar results were observed, so our custom NEST weightings and standard ANGSt catchments were used, and are reported here.

2.7. Data analysis

We tested for associations between socio-demographic and UGI variables using Spearman’s rank correlations. However, we also wanted to understand the strength of associations between ethno-racial/socio-economic status and UGI provision independently of human population density and so we performed a non-parametric partial correlation. We used a Mann-Witney *U* test to identify differences in the socio-demographic characteristics of LSOAs with high and low levels of UGI provision. For street trees we divided LSOAs according to median density (129 trees km⁻²), while accessibility was separated into high and low provision (more/less 50% of the area of the LSOA with good access), and greenspace quality was divided along its median score of 55.5. All statistical analyses were carried out in SPSS.

Spatial analysis was undertaken using GeoDa 1.6.7 (Anselin, Syabri, & Kho, 2006). Global univariate Moran’s *I* value derives spatial autocorrelation through correlating the variable against a spatially weighted predictor, thereby indicating the strength of spatial relationships throughout a sample, with local indicators of spatial association (LISA) visualising clusters. As we were interested in UGI distributions in relation to socio-demographics, we used bivariate Moran’s *I* and LISA maps with a spatially weighted queen contiguity-based predictor. This was done at a significance level of 0.05 and tested with 999 permutations, ensuring stability within the results and providing an ‘ad hoc’ sensitivity analysis (Anselin et al., 2006).

3. Results

3.1. Street trees

Street tree density was positively correlated with household deprivation ($r_s = 0.337, p < 0.01$), and remained so when accounting for population density ($r_s = 0.203, p < 0.01$) (Table 2, Fig. 4A). There were significant differences in household deprivation between LSOAs with high and low densities of street trees ($U = 4258.5, p < 0.01$,

$N = 218$) (Table 3). For ethno-racial groups, street tree density was negatively associated with the percentage of residents self-reporting as White ($r_s = -0.358, p < 0.01$) and positively associated with those self-reporting as Asian/Asian British ($r_s = 0.323, p < 0.01$) (Table 2, Fig. 4B,C). These associations remained when accounting for population density, with the proportion of White residents negatively associated ($r_s = -0.196, p < 0.01$), and the proportion of Asian/Asian British residents positively associated ($r_s = 0.162, p < 0.05$) (Table 2). LSOAs with above median street tree density were characterised by a significantly higher proportion of Asian/Asian British residents ($U = 4178, p < 0.01, N = 218$) (Table 3), and a lower proportion of White residents ($U = 4000.5, p < 0.01, N = 218$).

Spatially, household deprivation was clustered with street tree density ($I = 0.220, z = 6.6908, p < 0.001$) (Figs. 5 and 6A). In terms of ethno-racial groups, self-reporting White residents in LSOAs displayed spatial outliers ($I = -0.285, z = -8.788, p < 0.001$), while self-reporting Asian/Asian British residents displayed spatial clusters with street tree density ($I = 0.273, z = 8.255, p < 0.001$).

3.2. Neighbourhood greenspace accessibility

The total percentage of the city within 300 m of a greenspace was 65.6%. The proportion of an LSOA with accessible neighbourhood greenspace was weakly negatively associated with household deprivation ($r_s = -0.142, p < 0.05$) (Table 2, Fig. 4D). Additionally, LSOAs with fewer deprived households had a greater proportion of their area accessible to neighbourhood greenspaces ($U = 4645.5, p < 0.01, N = 218$) (Table 3). Accessibility was associated with ethno-racial groups. It was positively correlated with the proportion of residents who were White ($r_s = 0.241, p < 0.01$), but negatively correlated with the proportion of residents who were Asian/Asian British ($r_s = -0.235, p < 0.01$) (Table 2, Fig. 4E, F). LSOAs with higher accessibility had more White residents (and fewer Asian/Asian British residents; $U = 4321.5, p < 0.01, N = 218$) than those with low accessibility ($U = 4276, p < 0.01, N = 218$) (Table 3). When controlling for population density, associations between accessibility and household deprivation and ethno-racial groups were no longer significant.

Spatially, household deprivation and accessibility revealed spatial outliers ($I = -0.197, z = -6.209, p < 0.001$) (Figs. 5 and 6D). When accessibility was assessed against ethno-racial groups, self-reporting White residents in LSOAs were clustered spatially ($I = 0.258, z = 8.073, p < 0.001$), while those self-reporting as Asian/Asian British were not ($I = -0.237, z = -7.218, p < 0.001$) (Figs. 5 and 6E,F).

3.3. Greenspace quality

Greenspace quality was weakly positively associated with the proportion of residents self-reporting as Asian/Asian British ($r_s = 0.202$,

Table 2
Spearman correlations and non-parametric partial correlations for urban green infrastructure (UGI) and socio-demographics from the ONS (2011) census in Bradford, UK. ** indicate significant correlations at the 0.01 level, * at the 0.05 level.

	<i>N</i>	Spearman’s rho	Household Deprivation (0–4)	White (%)	Asian/Asian British (%)	Population Density (km ⁻²)
Street Tree Density (km ⁻²)	218	0.337**		-0.358**	0.323**	0.398**
Neighbourhood Greenspace Accessibility (%)	218	-0.142*		0.241**	-0.235**	-0.264**
Greenspace Quality (%)	203	0.034		-0.187**	0.202**	-0.08
	<i>N</i>	<i>df</i>	Partial Correlation – Controlling for Population Density			
Street Tree Density (km ⁻²)	218	215	0.203**	-0.196**	0.162*	
Neighbourhood Greenspace Accessibility (%)	218	215	-0.036	0.128	-0.127	
Greenspace Quality (%)	203	200	0.041	-0.171*	0.171*	

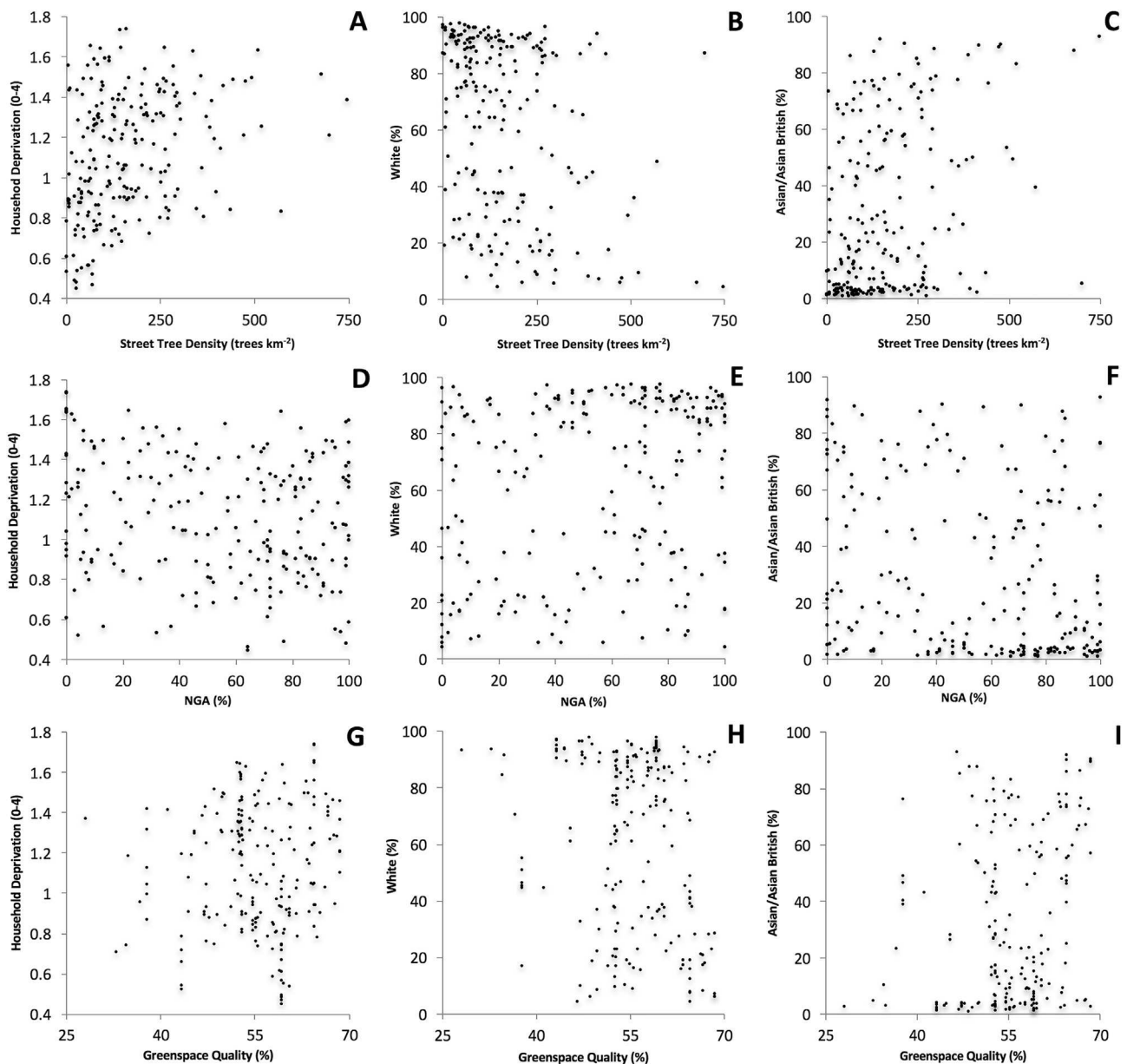


Fig. 4. Associations between socio-demographic variables (household deprivation, % White, % Asian/Asian British) and urban green infrastructure (UGI); street tree density (trees km⁻²), neighbourhood greenspace accessibility (% of the LSOA) and greenspace quality (a score per LSOA derived from the Natural Environment Scoring Tool).

Table 3

Differences in urban green infrastructure (UGI) metrics between LSOAs with human populations lying above and below median levels of household deprivation, % White and % Asian/Asian British residents. ** Indicates significance at a 0.01 level.

	Street Tree Density (km ²) n = 218			Neighbourhood Greenspace Accessibility (%) n = 218			Greenspace Quality (%) n = 203		
	Mean Rank High (> 129 street trees km ²)	Mean Rank Low (< 129 street trees km ²)	U	Mean Rank High (> 50%)	Mean Rank Low (< 50%)	U	Mean Rank High (> 55.5)	Mean Rank Low (> 55.5)	U
Household Deprivation (0–4)	125.1	94.2	4258.5**	122.1	99.6	4645.5**	107.6	96.3	4576.5
White (%)	127.1	91.5	4000.5**	122.5	93.0	4276**	105.7	98.2	4774
Asian/Asian British (%)	125.8	93.5	4178**	125.5	96.9	4321.5**	107.5	96.7	4604.5

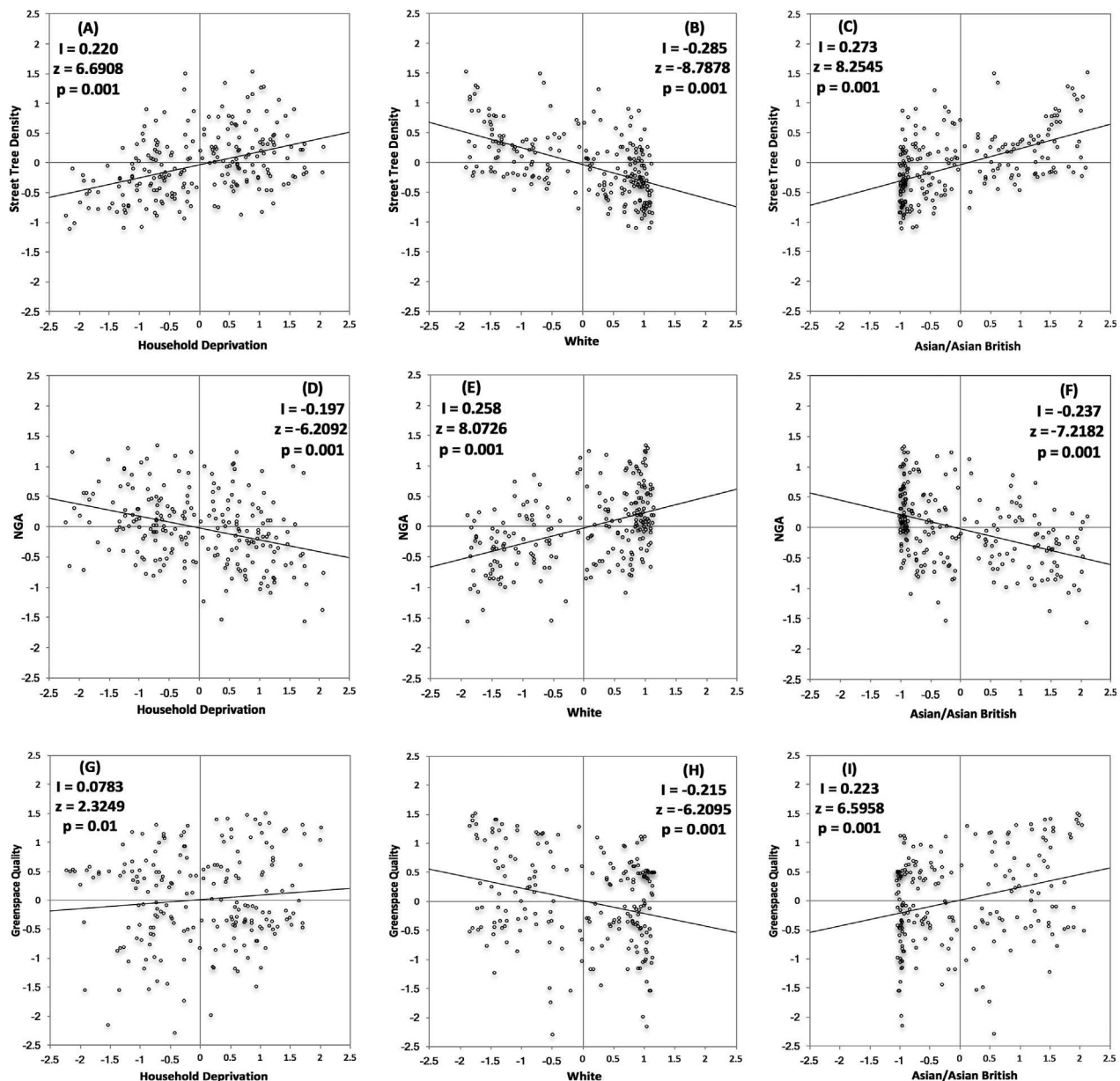


Fig. 5. Bivariate Moran's I scatterplots illustrating association between standardised values for each socio-demographic variable and spatially weighted urban green infrastructure (UGI) values, for: (A) Street tree density and household deprivation, (B) street tree density and White, (C) street tree density and Asian/Asian British, (D) neighbourhood greenspace accessibility and household deprivation, (E) accessibility and White, (F) accessibility and Asian/Asian British (G) greenspace quality and household deprivation, (H) greenspace quality and White, (I), greenspace quality and Asian/Asian British.

$p < 0.01$). Conversely, quality was negatively associated with self-reporting White residents ($r_s = -0.187$, $p < 0.01$) (Table 2, Fig. 4H, I). Associations with ethno-racial groups remained constant when controlling for population density ($r_s = -0.171$, $p < 0.05$; $r_s = 0.171$, $p < 0.05$ for White and Asian/Asian British respectively) (Table 2). However there were no significant differences in household deprivation or ethno-racial groups between LSOAs with high and low scores for greenspace quality (Table 3).

Spatially, household deprivation and greenspace quality were weakly associated ($I = 0.078$, $z = 2.325$, $p < 0.01$) (Figs. 5 and 6G). Ethno-racial groups were spatially associated with greenspace quality; LSOAs with residents self-reporting as White displaying negative spatial autocorrelation and predominately spatial outliers ($I = -0.215$, $z = -6.210$, $p < 0.001$). In contrast, Asian/Asian British self-reporting residents and greenspace quality were positively spatially autocorrelated and spatially clustered ($I = 0.223$, $z = 6.596$, $p < 0.001$)

(Figs. 5 and 6H,I).

4. Discussion

Urban green infrastructure includes a wide range of different natural and semi-natural features that are present in towns and cities. Reflecting this, we found a variety of associations between the distribution of publicly owned forms and characteristics of UGI, namely street trees and greenspace accessibility and quality, with household deprivation and ethno-racial groupings. Street tree density was higher in neighbourhoods with higher proportion of Asian/British Asian residents and levels of household deprivation. In common with other studies (e.g. Comber et al., 2008; Jones et al., 2009; Wolch et al., 2013), accessibility to greenspaces was higher in neighbourhoods with lower levels of deprivation and a lower proportion of ethnic minority residents. However, greenspace quality was largely unrelated to variation

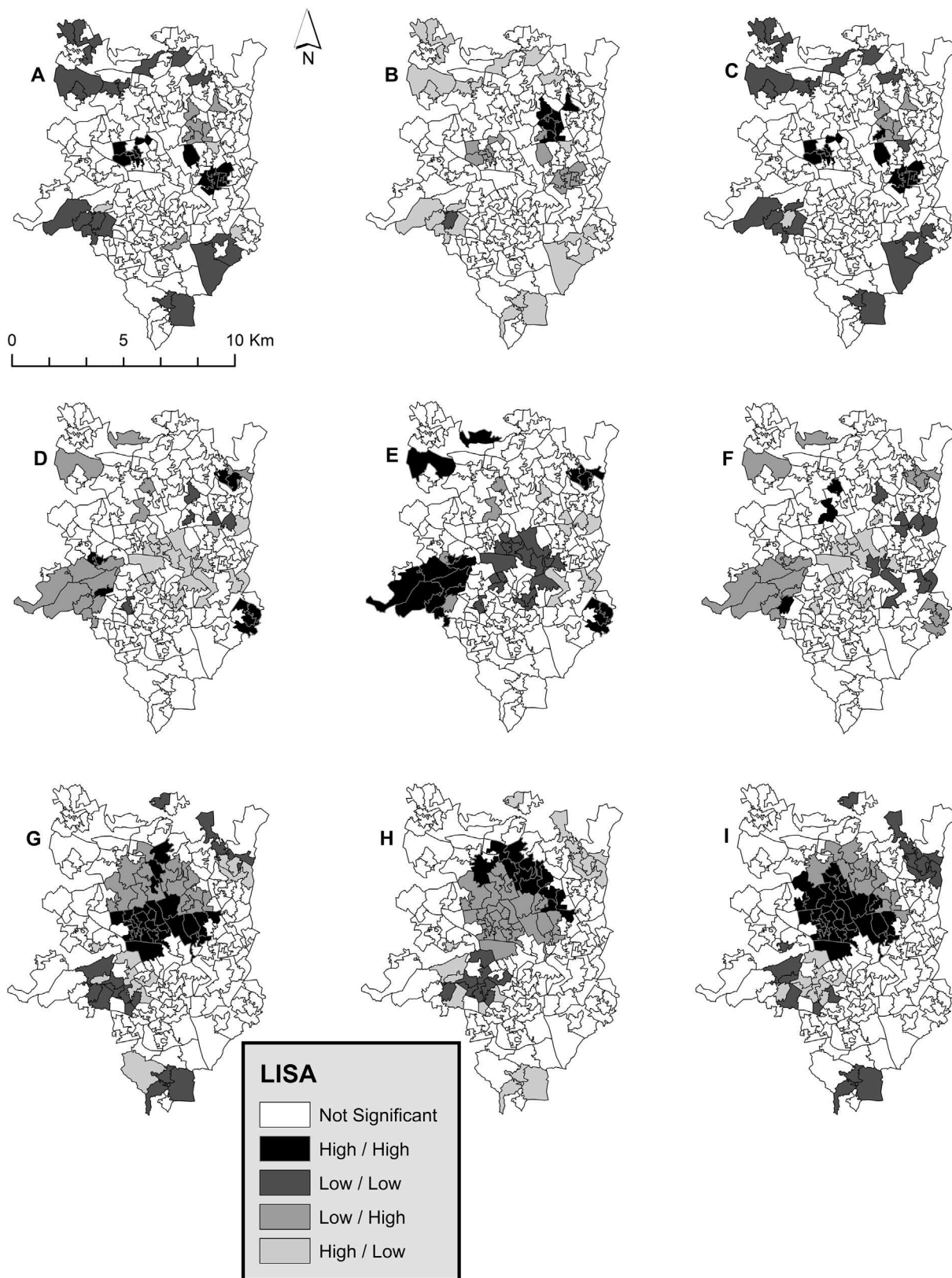


Fig. 6. Local Indicators of Spatial Association (LISA) maps. Figures display clusters between socio-demographics and spatially lagged predicted urban green infrastructure value at a pseudo-significance of 0.05, and tested for stability with 999 permutations. high/high (Socio-demographic/UGI), low/low values which indicate clustering, and low/high and high/low which indicate spatial outliers. (A) Street tree density and household deprivation, (B) street tree density and White, (C) street tree density and Asian/Asian British, (D) neighbourhood greenspace accessibility and household deprivation, (E) accessibility and White, (F) accessibility and Asian/Asian British (G) greenspace quality and household deprivation, (H) greenspace quality and White, (I), greenspace quality and Asian/Asian British.

in deprivation, ethno-racial group or population density, despite substantial spatial variation throughout the sample. For different forms and characteristics of UGI, there were, therefore, contrasting spatial patterns and distributions according to ethno-racial groups and deprivation. Our results emphasize the need to assess multiple forms and characteristics of UGI when wishing to understand the extent to which environmental public goods are distributed equitably across sectors of society. This is particularly important, considering different types of UGI can provide separate benefits independent from each other (Peschardt, Schipperijn, & Stigsdotter, 2012; Ulmer et al., 2016).

The forms and characteristics of our UGI indicators did vary by ethno-racial group and deprivation. Street tree density was higher in LSOAs with more Asian/Asian British households and which were more deprived. In contrast, accessibility was better in LSOAs with a greater proportion of White households and less deprived LSOA. The former finding contrasts with typical findings of environmental equity studies as we find the minority ethno-racial population and more deprived residents better-served by this form of UGI. Additionally, it contrasts the findings of Landry and Chakraborty (2009) and Kuruneri-Chitepo and Shackleton (2011); two studies which deal specifically with the equitable distribution of street trees and which found that the less affluent residents, and the ethno-racial minority in the case of Landry and Chakraborty (2009), were comparatively underserved.

There are several underlying causes for the variation in our distributions (Kendal et al., 2012; Landry & Chakraborty, 2009; Tooke et al., 2010). Street tree density is likely to be influenced by urban form (e.g. Pham, Aparicio, Landry, & Lewnard, 2017), such as the availability of roadsides where trees can grow. Although we did not include urban form in our analyses, one commonly used metric of urbanisation, population density, was strongly associated with our UGI indicators and provided an influential control variable for our partial correlations. Ethnicity, deprivation and population density can often co-occur, so studies that focus on why ethno-racial groups have poor access to greenspace increasingly incorporate how urban form and greenspace distribution are inter-related (Wolch et al., 2010; McConnachie & Shackleton, 2010). Assessing characteristics of UGI against other indicators, including urban form, road and building density may allow a greater understanding of their distributions (Pham et al., 2017) and the relationship between ethno-racial groups and UGI.

Across Bradford 65.6% of the city fell within 300 m of a neighbourhood greenspace and thus met the ANGSt criteria. Although not directly comparable in terms of methods used, our finding contrasts with 36% of the area of Sheffield (Barbosa et al., 2007) and 10.3% of Leicester (Comber et al., 2008) reported to meet ANGSt criteria. The figure for Bradford is, therefore, relatively high. However, given that accessibility as measured by a physical distance which will not always align with perceptions of accessibility (Jones et al., 2009; Maroko et al., 2009), it may be that ANGSt criteria are themselves not a suitable measure, and a more nuanced approach to setting accessibility standards (and compliance with those standards) is required (cf. Wilkinson, 1985).

Greenspace accessibility varied between ethno-racial groups and levels of deprivation. However, for this UGI characteristic, we found that neighbourhoods with a high proportion of Asian/Asian British residents and deprived households have less access to neighbourhood greenspaces than predominantly White, more affluent areas (cf. Boone et al., 2009; Shanahan et al., 2014; Wolch et al., 2013). Having access to recreational neighbourhood greenspace is important, particularly for children and the disabled (McEachan et al., 2016; Peschardt et al., 2012), as research has also found that the beneficial effects of greenspace may be stronger for those who actively use spaces (e.g. Bowler, Buyung-Ali, Knight, & Pullin, 2010). Our findings suggest that more disadvantaged groups have less access to suitable neighbourhood greenspaces, which may serve to widen health inequalities (Dadvand et al., 2014). In order to redress this imbalance and ensure that all communities have access to greenspace in their local areas, urban

planners could consider incorporating, the Natural England (2010), or equivalent, guidelines into their planning process. Ensuring adequate access to greenspace is a challenge in many dense urban areas due to a lack of suitable space (Haaland & van den Bosch, 2015). However creative solutions, which tailor spaces to the needs of the populace and utilise underused land, infrastructure or brownfield sites, which are often abundant in post-industrial cities, can play a role in achieving this.

Greenspace quality was unrelated to household deprivation and human population density. However, ethno-racial disparities were present. Neighbourhoods characterised by White residents were negatively associated with greenspace quality with the converse true for Asian/Asian British neighbourhoods. When assessed spatially, we observed that the spatial distribution of greenspace quality was independent from ethno-racial groups. Clusters of LSOAs with high quality greenspace provision occurred throughout the city regardless of the ethno-racial make-up of LSOAs (Fig. 6H,I). Nevertheless, the significant spatial clustering of greenspace quality (Fig. 5G,H,I) indicated that capturing quality should be an important part of any assessment of greenspace distribution and accessibility. For instance, across a range of studies and cities, despite a diversity of methods being employed, more disadvantaged residents tend to have fewer greenspace amenities and higher levels of incivilities, even if they do not have poorer access to greenspaces (Crawford et al., 2008; Hughey et al., 2016; Vaughan et al., 2013).

Since the latter half of the 20th century, immigration to the UK has been characterised by immigrants moving into low cost, densely populated areas which typically lack open spaces (Conway et al., 2010; Pham et al., 2012; Tooke et al., 2010). As a community becomes more established, this process may become self-perpetuating, with amenities, such as those based on community, society, religion or language, that an immigrant would value contained within these densely populated areas (Simpson, 2004). The inequality in greenspace accessibility that we report here may be a legacy of this process. Ethnic/racial groups utilise greenspaces in different ways which are theorised to develop for a variety of reasons. For instance Byrne and Wolch (2009) suggests exclusion/marginalization/discrimination or preferences developed through cultural heritage can help explain these differences. Our indicators of UGI distributions might, therefore, reflect differing methods of utilisation among ethno-racial groups, although our empirical data does not allow us to distinguish amongst possible causes (Lyytimäki & Sipilä, 2009).

Although evidence is limited in the UK, ethnic minorities are often overlooked in their environmental needs. Indeed, many feel a sense of exclusion from the countryside (Askins, 2009; Elvers et al., 2008) and inequitable access to urban green spaces may reinforce this (Comber et al., 2008). Hence in Bradford, the Asian/Asian British ethno-racial minority may not have integrated into neighbourhoods with better access to greenspaces due either to a perception of exclusion or because nearby UGI is not a priority when selecting places to live (Askins, 2009; Elvers et al., 2008).

Similar processes may explain accessible greenspace distributions relating to household deprivation levels, as more deprived residents are priced out from LSOAs with better access to public greenspaces (Conway et al., 2010; Jones et al., 2009; Pearce, 2003). Dadvand et al. (2014) found ethnic minority populations in Bradford were on average more deprived than White residents and they typically had worse access to greenery. Therefore, the synergy between household deprivation and LSOAs with a majority Asian/Asian British population and their limited access to neighbourhood greenspaces should come as no surprise. Locally, these distributions show improving the equity of accessibility to greenspaces and, therefore, the liveability of the city, prioritising the number of small, nearby greenspaces would likely help mitigate health inequalities to a greater extent than fewer, larger parks. The many pressures on, and demand for, space in urban areas makes this a challenge, but the potential health and wellbeing gains are substantial and

should not be ignored in land-use decision-making processes (Mitchell & Popham, 2008; White et al., 2016).

5. Conclusion

Assessing a variety of UGI forms and characteristics revealed different distributions in Bradford, further reinforcing the concept that equity in UGI distribution is strongly context, and indicator specific (e.g. Barbosa et al., 2007; Comber et al., 2008; Jones, Brainard et al., 2009; Kessel et al., 2009). Contrasting findings are likely to be a result of the forms and characteristics of UGI studied and the precise methodologies followed. For example in our assessment of greenspace accessibility, we accounted for the countryside and found many less deprived LSOAs on the outskirts of the city have sufficient access to greenspace via their proximity to the open countryside (c.f. Barbosa et al., 2007). Equally, given the generally higher coverage of privately owned UGI in less deprived areas (Shanahan et al., 2014; Tooke et al., 2010) our results would likely have been different if we had repeated our analyses to include private greenspaces, such as domestic gardens. However, we deliberately focussed on publicly owned and accessible UGI with the intention of assessing only UGI that was accessible to all residents. Publically accessible urban green infrastructure offers the opportunity to provide needs-based provision to more deprived residents, who will disproportionately benefit from it (Pham et al., 2012).

We are still some way from fully understanding and quantifying how forms and characteristics of UGI vary among socio-economic and ethno-racial groups. Doing this would require a national assessment of UGI equity issues using a consistent multi-indicator methodology which broadens information used beyond that easily accessible through census data. Furthermore, to confirm the interpretation of the results and understand, rather than outline, the distributions, future research could attempt to unpick causal relationships by making use of temporal data. This is key to tackling the issue, as in order to provide equitable access to UGI, it is important that policy-makers understand what drives inequitable distributions, perhaps helping to avoid counterproductive processes such as gentrification that can arise from well-intentioned interventions. Doing so remains a challenging proposition for such a multifaceted issue.

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