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Not all brownfields are equal: A typological assessment reveals hidden green space in the city

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HIGHLIGHTS

- A novel typology identifies 26 brownfield types in Greater Manchester, UK.
- >50% of brownfield land is vegetated, contributing to green infrastructure.
- Brownfield with uneven topography, irregular shape, and those containing a water body are highly vegetated.
- Impervious brownfield types are clustered in densely built-up urban areas.
- Highly vegetated brownfield are widely distributed across the urban region.

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ABSTRACT

While the role of urban green space in mitigating environmental hazards and enhancing urban resilience is widely recognised, the current or potential contribution of brownfield land to urban green infrastructure and ecosystem services has been largely overlooked by planning legislation. The perception of brownfield as low value spaces has instead driven a focus on brownfield-first redevelopment, and thus, this dynamic resource is quickly being lost. This research, based on GIS and remote sensing data, develops a novel hierarchical brownfield classification methodology to understand the nature and distribution of brownfield, using k-means clustering of several physical attributes, which can be used for a range of objectives and is widely applicable to post-industrial cities. Application of the methodology to the case study, Greater Manchester, UK, produced a typology of twenty-six brownfield types with distinct characteristics and differing spatial patterns across the city. Land cover analysis reveals that over half (51%) of brownfield land is vegetated (comprising 27% trees and shrubs, 24% grass and herbaceous vegetation), highlighting the significant 'hidden' green space present on brownfield. Brownfield sites traditionally perceived as difficult to develop (e.g. those with uneven topography, irregular shapes, or a water body), are particularly highly vegetated. Predominantly pervious types are widely distributed across the conurbation, including in built-up areas, which are a principal target for redevelopment, and thus highly vegetated brownfields are likely being lost undetected. Brownfield land is evidently a valuable dynamic resource in post-industrial cities and redevelopment should be planned at the city-scale to ensure careful strategic selection of sites for redevelopment, greening, or interim use based upon their characteristics and location.

1. Introduction

The presence and extent of brownfield in post-industrial cities is considerable, unequally distributed, and largely concentrated in areas of previous industrial activity and built-up areas (Longo & Campbell, 2017). Brownfield has been described as primarily left over from commercial/industrial activities in urban and suburban areas, and is associated with past mining, agricultural, and forestry activities in *peri*-urban and rural areas (Grimski & Ferber, 2001). Several terms are used to describe such previously developed land, including wasteland, vacant land, derelict land, wildscape, drosscape, and vacant lots (Bonthoux, Brun, Di Pietro, & Greulich, 2014; Kim, Miller, & Nowak, 2018). Whilst no universally accepted definition of previously developed land exists (Alker, Joy, Roberts, & Smith, 2000a), these terms suggest that it is a

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homogenous land use and largely evoke negative perceptions of unsafe or barren spaces of little ecosystem service or environmental value that have an adverse impact upon the local community and environment (Kim et al., 2018). In reality, urban brownfields are recognised by conservationists, ecologists, and green space planners as diverse spaces containing water and vegetation at various stages of succession alongside the relics of past development, providing important ecosystem services (Francis & Chadwick, 2013; Kim, 2016; Mathey, Rößler, Banse, Lehmann, & Bräuer, 2015), contributing to urban biodiversity (Bonthoux et al., 2014), and possessing potential value as open amenity space (Kamvasinou, 2011; Rall & Haase, 2011). However, this is often largely overlooked by planning legislation (Mathey et al., 2015).

A global drive towards sustainable development has instigated regulation to prevent urban sprawl, which has increased urban redensification (United Nations, 2019). This has led to a focus on the regeneration of urban brownfield for residential and commercial purposes to reduce greenfield development (Oliver, Ferber, Grimski, Millar, & Nathanail, 2005). While it is clear that the regeneration of brownfield can provide social, economic, and environmental benefits (Chen, Hipel, Kilgour, & Zhu, 2009), a brownfield-first approach can lead to high density developments (Davies et al., 2011; Dixon & Adams, 2008) in the absence of park creation, particularly in low-income areas where brownfield is more prevalent (Sister, Wolch, & Wilson, 2010). Redevelopment of brownfield will replace pervious and vegetated areas with built-up land, thereby resulting in a loss of ecosystem services and reduced urban resilience to climate-related hazards, such as flooding and heat waves (Meerow & Newell, 2017; Robinson & Lundholm, 2012). This has stark environmental equity implications for cities, where the drive for brownfield-first redevelopment fails to consider the current or potential role that brownfield could play by providing green space and ecosystem services, benefits which are much needed in urban areas, particularly where housing density is high (Davies et al., 2011). As such, the lack of robust spatial data and detailed knowledge on brownfield character may inhibit the strategic planning of brownfield redevelopment across cities, with the exception of exemplar sites or areas in major European cities (Franz, Güles, & Prey, 2008).

The physical structure of different land use types and their associated open and green space extent, coupled with their spatial distribution and location within the urban fabric, can define their potential ecosystem service provision (Arlt, Hennersdorf, Lehmann, & Thinh, 2005). Looking at the physical structure of individual land use types such as brownfield more closely may provide a more detailed indication of their provision of ecosystem services (Lehmann, Mathey, Rößler, Bräuer, & Goldberg, 2014). Furthermore, linking land cover extent and vegetation structure to individual land use types may also enable more detailed monitoring of a city's green inventory (Mathey, Hennersdorf, Lehmann, & Wende, 2021). In order to improve social wellbeing and environmental quality, urban planning should consider the potential of brownfields to provide new urban green space (Mathey & Rößler, 2021). To support this, appropriate information identifying the extent and location of a city's brownfields is required; brownfield registers or land-use databases are examples of the data available in many cities (Mathey & Rößler, 2021). Furthermore, details of the physical structure of brownfield, including vegetation structure and the extent of impervious surfaces, as well as size and shape, will help to evaluate their current or potential ecosystem service provision (Mathey & Rößler, 2021). Lehmann et al. (2014) and Mathey et al. (2015) introduce typologies based on the successional stages of brownfield and relate this to ecosystem service provision.

It is therefore imperative to understand more about brownfield land and its potential to improve urban resilience in response to social and environmental challenges and ensure sustainable land use strategies (Chen et al., 2009) whilst avoiding maladaptation. As a first step, this requires a systematic remote approach using a broadly applicable methodology for the identification and characterisation of all brownfield sites across a city. Whilst there has been research on planning tools for infill development (see Schetke, Haase, and Kötter (2012)), there is a lack of research examining the total regional stock of brownfield that considers measured physical attributes and locations of all sites, that allows their visualisation within the urban fabric. This can be used to identify potential redevelopment opportunities, priority for remediation, and indicate current and future potential physical state and ecosystem service attributes. When combined with socio-economic and risk factors, this would provide stakeholders with a valuable tool to assist in understanding the multiple and complex issues related to brownfield in order to make evidence-based decisions (Alker, Barrett, Clayton, & Jones, 2000b; Dasgupta & Tam, 2009).

Whilst brownfield targeted for redevelopment is often perceived as a single entity within a wider typology of urban land use or unused spaces (Kim et al., 2018; Rupprecht & Byrne, 2014), for instance in land use maps, several brownfield classification systems also exist and are used in decision-making which typically focus on identifying suitability or priority for redevelopment (Alker et al., 2000b; Dasgupta & Tam, 2009). Existing brownfield classification systems are generally based on attributes related to stakeholder objectives for redevelopment, including site-based (e.g., cost, contamination, size, site use, location) and contextual attributes (e.g., neighbouring land uses or socio-economic aspects) (Alker et al., 2000b; Dasgupta & Tam, 2009; Thomas, 2002). Brownfield redevelopment often equates to reducing harm, and thus classifications have been based on remediation time and financial or economic factors, rather than physical and vegetation structure characteristics (Alker et al., 2000b; Dasgupta & Tam, 2009). Such approaches do not fully consider the diverse nature of brownfield (Kim et al., 2018; Rupprecht & Byrne, 2014).

Many major cities utilise ecological mapping to provide an ecological basis for planning activities that may impact upon the habitats and local environment (Freeman & Buck, 2003). This attempts to objectively establish the spatial organisation and structure of habitats within the landscape (Beauchesne, Ducruc, & Gerardin, 1996). One example is the phase one habitat survey in Great Britain, which is a standardised system for classifying and mapping wildlife habitats (Committee, 2010). This has been adapted to include habitats common in the urban landscape and brownfield sites (e.g., amenity grassland, tall ruderal and ephemeral/short perennial habitat classes) for urban planning purposes, and is a common requirement for new developments which is valuable for habitat conservation (Committee, 2010). Site-based ecological mapping, phase one habitat surveys, and land use mapping, for example, are valuable for examining biodiversity and the ecological aspects of individual brownfield sites before development and identifying the designated uses of a city's land parcels. However, a remote region-scale assessment and typology of brownfield which identifies location, land cover and landscape metrics could be used as an initial indicator for ecosystem service and green space provision, ecological planning, and further analysis.

Socio-ecological aspects such as community use or ecosystem characteristics have been incorporated into typologies of brownfield in recognition that previously developed land can present social, ecological, and environmental benefits (Kremer, Hamstead, & McPhearson, 2013; Mathey et al., 2015). This is an important advancement, and these typologies typically have very broad groups, for example 'post-industrial', 'natural' or 'vacant' types, each of which may contain brownfield sites with wide-ranging physical and/or vegetated states (Kim et al., 2018; Moser, Krylov, De Martino, & Serpico, 2015). In addition, these typologies may be applied to a limited number of case study sites, since they employ methods that require significant resources to investigate the characteristics of each site, and it may therefore not be practical or efficient to assess all sites across a region or city.

A brownfield classification methodology should include site-based attributes that are transferable and can be easily assessed to provide a comprehensive typology of brownfield sites (Kremer et al., 2013). The most useful attributes are those which can be broadly applied and readily evaluated remotely at a city scale, which provide relevant information regarding both redevelopment potential and current and future value of the site in terms of green infrastructure and ecosystem service provision. Common site-based attributes that can be applied to any urban land parcel include land cover, size, shape, and topography, which may provide indicators for strategic re-use of brownfield whilst supporting urban sustainability and resilience (Kremer et al., 2013).

Assessment of land cover has been incorporated into land use and brownfield typologies to aid site identification and monitor land use change (Kremer et al., 2013; Moser, Krylov, De Martino, & Serpico, 2015). As noted above, however, these studies may classify brownfield as a single land use type or into broad groups within which members may have wide-ranging physical characteristics. In other studies, the inclusion of land cover characteristics has allowed assessments to be made with regard to redevelopment potential (Thomas, 2002), the feasibility of short-term and long-term uses in terms of site safety and accessibility (Rall & Haase, 2011), provision of open space for future use (Kim, 2018), ecosystem services provision (Mathey et al., 2015), and successional age (Schadek, Strauss, Biedermann, & Kleyer, 2009), where, Lehmann et al. (2014), and Mathey et al. (2015) have identified three fundamental stages of natural succession on brownfields. However, there has not been a remote city scale examination of brownfield land cover and landscape metrics encompassing site-level assessment of the complete stock of brownfields.

In addition to land cover, the physical characteristics of brownfield sites, including size, shape, and topography, are important factors that determine both development potential and ecosystem service benefits. Site size and shape irregularity were found to be the two most common deterrents to redevelopment of vacant land in US cities (Pagano and Bowman (2004). Smaller sites, particularly those with an irregular shape, are challenging to develop and often require constructors to acquire multiple sites or build high-density developments (Tiesdell & Adams, 2004). Indeed, whilst development potential is less attractive for small irregularly shaped sites, they may provide important opportunities to enhance green infrastructure and habitat connectivity (Kremer et al., 2013; Miyawaki, 1998). For example, irregularly shaped sites have a greater perimeter, where the edge effect results in niche habitats with a dominance of edge tolerant species (Francis & Chadwick, 2013), and thus they support greater species richness (Gonzalez et al., 2010). Furthermore, since public perceptions of and willingness to use sites can increase with size (depending on vegetative state) (Rall & Haase, 2011), and people are more reluctant to use smaller sites (Palliwoda & Priess, 2021), this may encourage vegetation succession and urban woodland establishment, dependant on substrate conditions and access (Francis & Chadwick, 2013). Uneven or steep topography is a key barrier to the redevelopment of brownfield (Kim et al., 2018; Northam, 1971; Pagano & Bowman, 2004), and can increase redevelopment costs (Nogués & Arroyo, 2016). However, the low redevelopment potential for sites with uneven or steep topography, together with reduced management regimes compared to level ground surfaces, means that such sites can promote tree canopy cover and high-quality green space (Davies et al., 2008).

In response to a paucity of existing typologies that are suitable for indicating the distribution of ecosystem service, or green space provision, of brownfield at a city-scale (whilst others have often been useful for identifying the suitability or priority of brownfields for redevelopment), here we present a novel method for classifying urban land parcels which is applied to develop a brownfield typology that: (i) considers the diverse physical characteristics of brownfield land (ii) can be used as an initial indicator for a wide range of objectives and (iii) is widely applicable to post-industrial cities. This article documents the development of methods that enable a remote city-scale typological assessment of brownfield for the case study of Greater Manchester, UK. Remote sensing, geospatial analysis, and statistical methods are applied to several attributes (land cover, size, shape, and topography) to understand the nature and distribution of the different types of brownfield identified. This city-scale assessment could usefully act within a multilevel approach to screen sites for selection and further evaluation, combined with contextual information and other criteria, to enable more efficient resource allocation (Alker et al., 2000b; Dasgupta & Tam, 2009).

2. Methods

2.1. Study area

Greater Manchester in the North West of England, UK, is an extensive metropolitan area (1276 km^2) encompassing ten local authority districts (Fig. 1) with a population of 2.8 million residents (Greater Manchester Combined Authority (GMCA), 2019). A polycentric conurbation, the cities of Manchester and Salford form the urban core, with other urban centres distributed across the city region (GMCA, 2019). Originating from several unconnected towns, each with significant commercial and industrial heritage, Greater Manchester emerged as these towns grew and amalgamated to form the urban expanse that exists today (Barlow, 1995). Greater Manchester's prolific industrial past has left a legacy of many brownfield sites widely distributed across the conurbation (Barlow, 1995). The pattern of brownfield sites in the region reflects the history of the satellite towns (Barlow, 1995).

2.2. Overview of approach

This study adopts a remote sensing-GIS approach to develop a typology of brownfield sites for Greater Manchester based on land cover and landscape metrics. This required: (i) the creation of a composite brownfield geospatial database, (ii) the selection of criteria and geospatial datasets to enable characterisation of the database, (iii) the construction of a brownfield typology employing cluster analysis, and (iv) the mapping of the typology across the urban matrix. Spatial processing and analysis was conducted using Esri ArcMap 10.6.

2.3. Brownfield spatial database

The first step was to create a novel brownfield spatial database of polygon locations based on brownfield register data. As the most recent available registers (Ministry of Housing Communities, Local Government. (2017), 2017) only include sites where residential development is achievable in a specific time frame, earlier registers were attained from the 2010–2012 National Land Use Database of Previously Developed Land (NLUD-PDL) (Homes and Communities Agency (HCA). (2014)). The brownfield sites included from the 2017 data contained previously developed land that local planning authorities consider to be appropriate for residential development on land which is suitable, available, >0.25 ha or suitable for 5 dwellings, where this is achievable within 15 years (criteria set out in Regulation 3 of the Town and Country Planning (Brownfield Land Register) Regulations 2017) (Ministry of Housing Communities, Local Government. (2017), 2017). The brownfield sites included from the 2010–2012 data contain four categories: A – previously developed land now vacant, B – vacant buildings, C – derelict land and buildings, D – previously developed land or buildings allocated in local plan (Homes and Communities Agency (HCA). (2014); Tang & Nathanail, 2012). The brownfield databases exclude current agriculture, forestry, mining, landfill, recreation grounds (HCA, 2014; Tang & Nathanail, 2012), and land in built-up areas such as residential gardens, parks, and allotments (Ministry of Housing Communities and Local Government, 2012). In the absence of complete polygon shapefile data at the time of analysis, the spatial database was created by digitising the 2017 brownfield register point locations using Ordnance Survey (OS) Mastermap topography layers (Ordnance Survey, 2017b), and combining this with the 2010–2012 NLUD-PDL using overlay analysis. Sites developed in the period 2010–2017 were identified using the OS Mastermap Topographic layers from October 2010 and December 2017 in conjunction with aerial imagery (ESRI, 2017; Getmapping, 2018) in ArcGIS 10.6, and removed from the database.

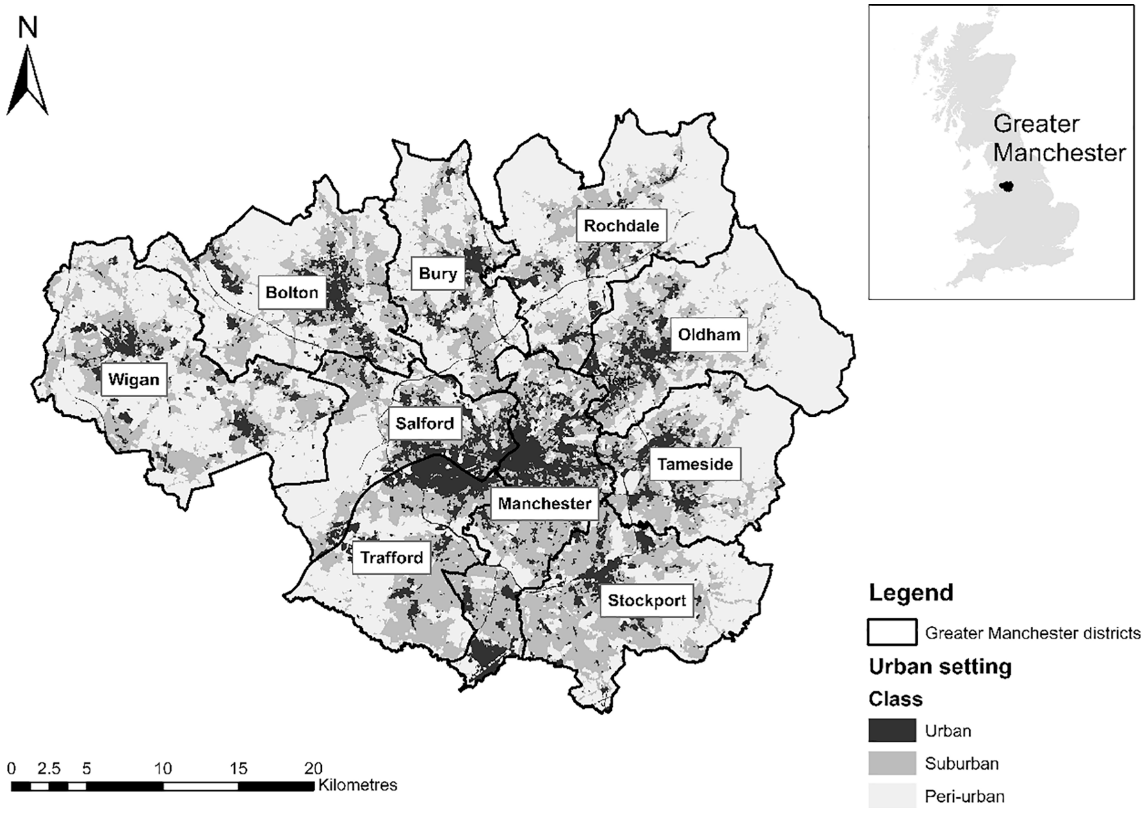

Fig. 1. Greater Manchester and the ten districts. Great Britain base map is © Crown Copyright/database right (2021). An Ordnance Survey/EDINA supplied service. Greater Manchester district boundary data, ONS (2018). Urban setting classes based on (Rowland et al., 2017).

2.4. Landscape metrics and land cover

The brownfield characterisation was based on landscape metrics (size, shape, slope) in combination with land cover, where the use of widely accessible criteria enables transferability of the method. These criteria are typically seen as key indicators for ecology and ecosystem service provision to help understand landscape structure, configuration and composition (Gökyer, 2013; Syrbe & Walz, 2012; Uuemaa, Mander, & Marja, 2013); sustainable planning and development to characterise land use patterns, processes, and consequences (Horning, 2008); and conventionally, indicating determinants of development potential by indicating potential physical barriers (Pagano & Bowman, 2000). Site size was established using geometric calculations for the brownfield spatial database. Three shape metrics were calculated: perimeter-area ratio (PAR), area weighted mean shape index (AWMSI), and mean patch fractal dimension (MPFD) (Wu, 2004). To determine slope, the Ordnance Survey Terrain 5 digital terrain model dataset (Ordnance Survey, 2018) was clipped to each brownfield boundary and mean slope was calculated using the ArcGIS zonal statistics tool.

High resolution (25 cm) orthorectified colour aerial imagery, in 1 km^2 tiles, with image capture dates ranging from 2009 to 2016, was obtained from Getmapping Aerial Photography Data Collection through the Aerial Digimap service (Getmapping). Aerial image capture dates for ‘leaf on’ and ‘leaf off’ seasons were classified separately to account for the spectral differences evident for vegetation during different seasons. Object-based image analysis (OBIA), also known as segmentation (Campbell, 2006), was used to identify potential land cover classes. This was followed by a supervised classification approach using the maximum likelihood automatic classifier (MLC) (Cadenasso, Pickett Steward, & Schwarz, 2007). Once segmented, training samples were selected for six land cover classes: trees and shrubs, grass and herbaceous vegetation, bare earth, water bodies, impervious surfaces, built structures, and shadow (shaded areas where land cover could not be identified). The MLC was calibrated to take into consideration shape, size, colour, rectangularity, compactness, and mean and standard deviation digital number of each segment using standard input fields (Dey, Zhang, & Zhong, 2010).

Brownfield sites often contain the remains from past development including built structures, hard surfaces, rubble, and debris (Gilbert, 1995), where spectral confusion is common among such land cover classes (Lu & Weng, 2007). The classified images were therefore amalgamated with ancillary data to minimise misclassifications (Lu & Weng, 2007), using OS Mastermap Topography Layers (Ordnance Survey, 2017a) to identify buildings, man-made surfaces, and water bodies. The completed land cover classification permitted the calculation of land cover percentages for each brownfield. Accuracy assessment, facilitated by validating 1200 sample points using the high-resolution imagery, indicated the OBIA and classification procedure was 94 % accurate, above the widely cited satisfactory result of 85 % for image classification (Foody, 2008; Thomlinson, Bolstad, & Cohen, 1999). See supplementary materials S1 for a confusion matrix reporting accuracy by land cover class.

2.5. Creation of typology

The brownfield typology was based on a hierarchical classification produced using sequential applications of the k-means clustering algorithm in IBM SPSS Statistics for Windows, Version 27.0. K-means cluster analysis has been effectively used in urban typological research (Gil, Beirão, Montenegro, & Duarte, 2012) and geodemographic studies (Harris, Sleight, & Webber, 2005; Vickers & Rees, 2007). The k-means clustering method is an iterative method based on the error sum of squares measure, where the algorithm relocates each case (or brownfield data) between clusters or groups to establish improvements in sum square deviations in each cluster (Vickers & Rees, 2007). Clusters form where the greatest improvements are established, which minimises the variability within each cluster and maximises the variability between clusters (Frey, 2018). This process is repeated until no further improvements for cases are possible (Vickers & Rees, 2007).

The brownfield criteria input into the clustering algorithm were the landscape metrics and the percent land cover (the six land cover classes, total vegetated and total impervious) described above. The input data was standardised using z-scores due to the different measurement scales of the variables (Mohamad & Usman, 2013). The data was initially analysed from a starting point of two to ten clusters, where these solutions were then assessed using two metrics to determine the optimal starting solution. The Calinski-Harabasz index is the ratio of the sum of between-cluster dispersion and within-cluster dispersion for all clusters, where the greater the score, the more suitable the performance (Frey, 2018). The second metric evaluated the range in the size of cluster memberships for each initial cluster solution, where a low distance to the mean cluster membership is optimal (Vickers & Rees, 2007). Where multiple solutions performed well on both assessments, the solution with fewer clusters was chosen (Frey, 2018).

The distinctiveness of emerging groups were evaluated quantitatively using analysis of similarities (ANOSIM) from the PAST statistics package (Hammer, 2019), confirmed by examining high resolution aerial imagery (ESRI, 2017), and one of three actions taken. First, clusters with high dissimilarity (ANOSIM $R >= 0.25$ and $P < 0.05$) were identified as a distinct brownfield type. Visual inspection confirmed differences (to all other clusters). Second, clusters with low dissimilarity (to each other – ANOSIM $R < 0.25$ and $p > 0.05$) were merged to form a single brownfield type. Visual inspection of aerial images confirmed a lack of qualitative differences between the clusters. On the first and second pass through clustering, large groups ($n > 50$ % mean cluster membership (e.g. initial sites/optimal cluster solution)) (Vickers & Rees, 2007) were separated out and re-passed through the full clustering process. A workflow for the k-means clustering process is presented in supplementary material S2. A three-tier hierarchy was chosen to create an accessible and compact brownfield typology that is logical and easy to interpret, facilitating transferability of the method. After the third tier of the hierarchy was formed, all data from each cluster was profiled statistically and visually (aerial image interpretation) to allow the naming and description of the brownfield typology.

2.6. *Mapping the brownfield typology*

Spatial analysis of the brownfield typology, using point density analysis in ArcGIS, was undertaken to explore the distribution patterns of different brownfield types in Greater Manchester. The geographical distribution of the brownfield typology was also assessed using a reclassified 2015 land cover map for the UK (LCM2015) (vector GB), released in April 2017 (Rowland, Morton, Carrasco, McShane, O'Neil, & Wood, 2017). The LCM2015 dataset identifies urban and suburban areas, and several other habitat classes such as grasslands and agricultural land (Rowland et al., 2017). Any class not considered to be a built-up (urban and suburban) area was reclassified as *peri*-urban resulting in a three-class land cover map for Greater Manchester.

3. Results

3.1. *Spatial distribution, landscape metrics and land cover*

The spatial distribution of Greater Manchester brownfield is presented in Fig. 2, with a summary of the associated landscape metrics and land cover types presented in Table 1 and Fig. 3, respectively. In total, 2197 brownfield sites (3161.55 ha; 2.48 % of Greater Manchester area) were included in the spatial database, comprising 1108 urban sites (1101.70 ha; 6.14 % of urban area), 850 suburban sites (681.21 ha; 1.68 %), and 239 *peri*-urban sites (1378.71 ha; 2.00 %). Brownfield size varies widely, ranging from<0.1 ha to a substantial 268.29 ha, with a mean area of 1.44 ha. All Greater Manchester districts contain both larger brownfield sites (>10 ha), and multiple small sites (<0.1 ha). The topography of the sites is complex, as is common for brownfield (Alker et al., 2000a). Whilst the majority of sites have a mean slope below 5 degrees, >10 % (of sites) have a mean slope over 5 degrees, with 2.5 % exhibiting a mean slope of 10 degrees or more, and relatively few with a mean slope>15 degrees. Results from shape metrics emphasise the diverse brownfield geometry, from very compact to highly irregular and complex sites.

With respect to land cover, Greater Manchester brownfield land is dominantly pervious (58.72 %, 1856.5 ha) and significantly vegetated (51.25 %, 1620 ha). Vegetation is approximately evenly split between trees and shrubs (27.24 %), and grass and herbaceous plants (24.01 %). Bare earth contributes 6.16 %, and water 1.31 % of land cover. The

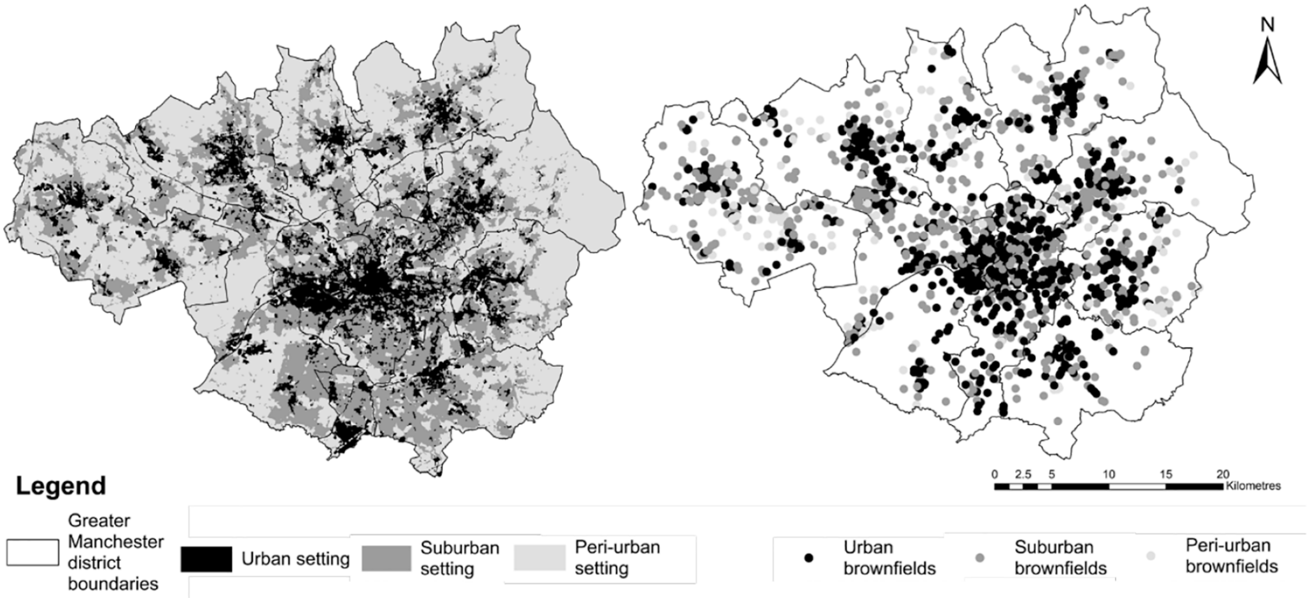

Fig. 2. A spatial database of brownfield sites in Greater Manchester. Greater Manchester district boundary data, ONS (2018). Urban zones from reclassified land cover map 2015 (Rowland et al., 2017) © NERC (CEH) EDINA Digimap Ordnance Survey Service.

Table 1
Descriptive statistics for landscape metrics of brownfield sites in Greater Manchester and the ten districts (depicted in Fig. 1). (n = number of brownfields, PAR = perimeter-area ratio, AWMSI = area weighted mean shape index, and MPFD = mean patch fractal dimension).

Metric	Statistic	GM Total	Bolton	Bury	Manchester	Oldham	Rochdale	Salford	Stockport	Tameside	Trafford	Wigan
Sites	**n**	2197	189	109	505	164	166	410	105	216	81	252
Area (ha)	**Sum**	3161.6	291.3	229.7	520.3	245.1	155.1	389.2	125.2	183.8	103.6	918.2
	Min	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Max	268.3	76.7	28.0	71.7	42.2	14.3	57.0	16.1	19.0	28.8	268.3
	Mean	1.4	1.5	2.1	1.0	1.5	0.9	1.0	1.2	0.9	1.3	3.6
	Standard deviation	7.4	5.9	4.2	3.9	3.7	1.8	3.4	2.4	1.6	3.3	19.3
Slope (degrees)	**Min**	0.0	0.2	0.2	0.2	0.0	0.3	0.1	0.2	0.4	0.1	0.2
	Max	25.4	17.5	21.6	17.0	25.4	13.6	15.0	24.8	19.2	4.2	14.0
	Mean	2.7	3.2	3.7	2.1	4.1	3.1	2.2	3.4	4.1	1.5	2.0
	Standard deviation	2.6	2.5	3.5	2.1	3.6	2.4	2.1	3.2	3.3	1.0	1.5
PAR	**Min**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.8	0.5	0.2	0.5	0.3	0.5	0.8	0.4	0.5	0.3	0.5
	Mean	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Standard deviation	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
AWMSI	**Min**	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
	Max	10.2	3.2	2.4	3.3	3.3	3.7	10.2	2.5	3.7	3.9	6.0
	Mean	1.4	1.4	1.4	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4
	Standard deviation	0.4	0.3	0.2	0.3	0.3	0.3	0.5	0.2	0.3	0.4	0.5
MPFD	**Min**	1.2	1.3	1.3	1.2	1.3	1.3	1.2	1.2	1.3	1.3	1.2
	Max	1.9	1.7	1.5	1.7	1.6	1.7	1.9	1.6	1.7	1.6	1.7
	Mean	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
	Standard deviation	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

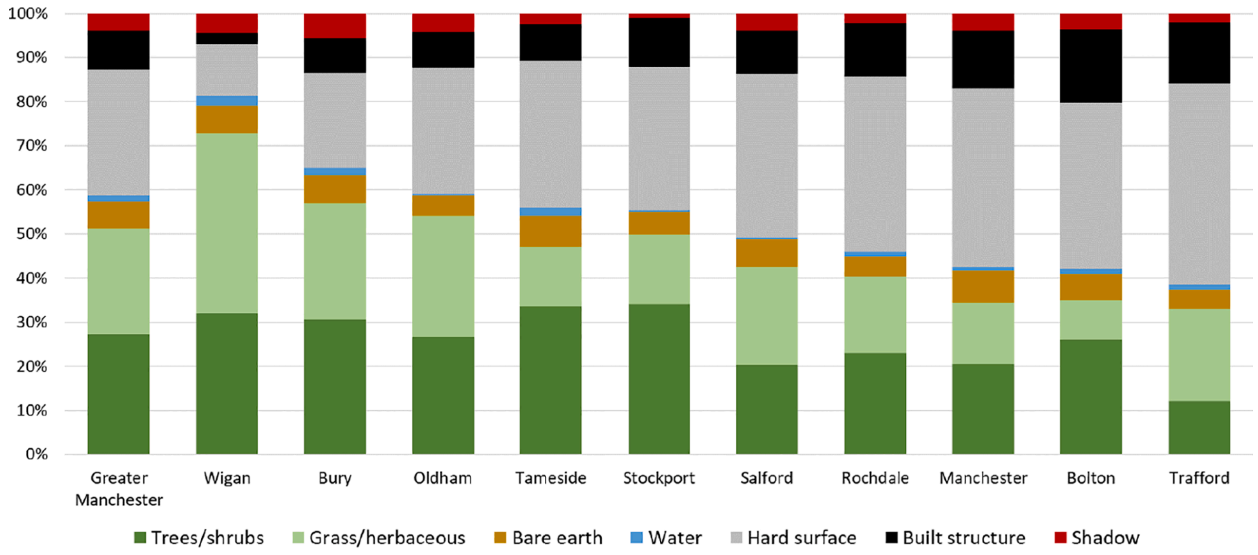

Fig. 3. Land cover statistics for brownfield sites in Greater Manchester and districts. Districts are presented in ranked order based on the ratio of pervious to impervious land cover types.

impervious land cover types include hard surfaces covering 28.62 % and buildings accounting for 8.82 %. Shadow obscuring true land cover is minimal in the classification (3.84 %).

3.2. Brownfield typology

The three-tier hierarchical typology identified twenty-six brownfield types distinguished by their land cover characteristics and contrasting or complex landscape metrics (Fig. 4). A description of each of the brownfield types including aerial images is presented in the supplementary materials S3.

The typology clearly divides brownfield into two distinct primary groups of predominantly impervious (1275 sites, 1,321 ha) and predominantly pervious (922 sites, 1841 ha) sites (Fig. 4). At tier two, the

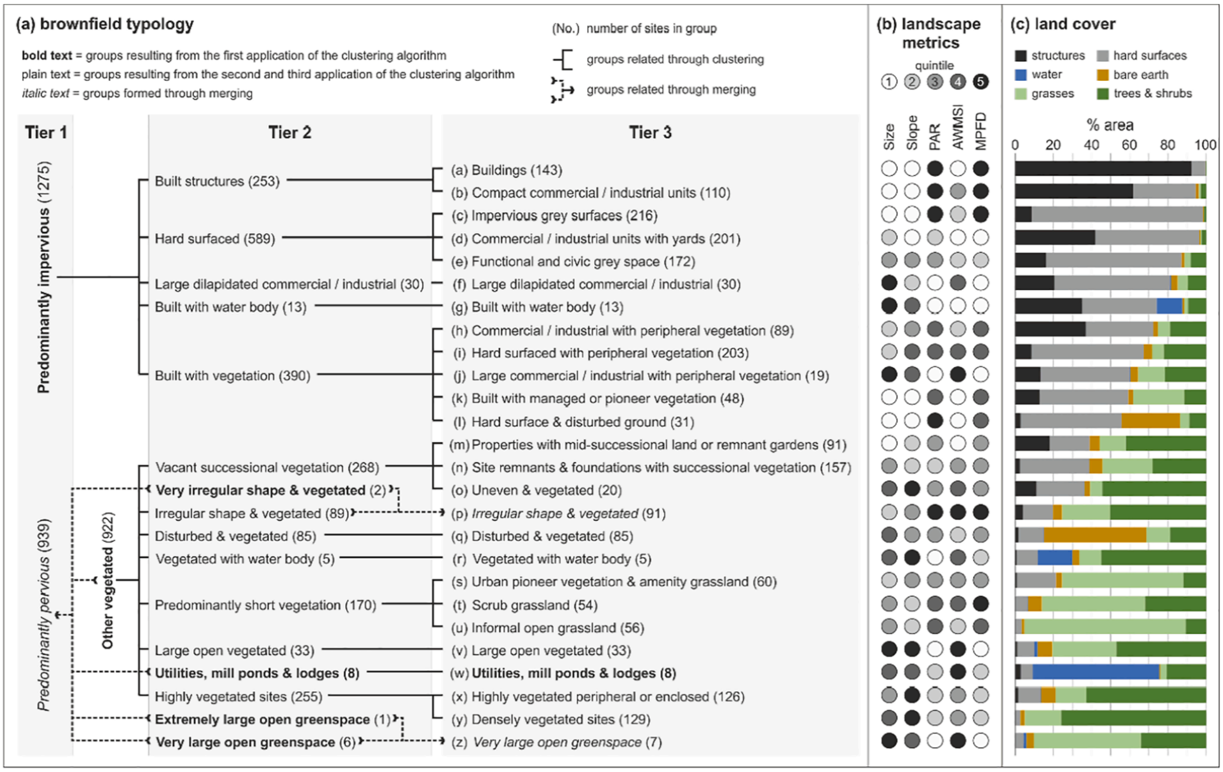

Fig. 4. (a) Brownfield hierarchical typology, with clusters (and types within clusters) presented in ranked order based on the proportion of impervious land cover (b) mean landscape metric quintile groups (c) mean land cover distribution. (Number of brownfields in parentheses, PAR = perimeter-area ratio, AWMSI = area weighted mean shape index, and MPFD = mean patch fractal dimension).

clustering of predominantly impervious brownfield distinguishes between sites dominated by built structures, hard surfaces, and those with some vegetation. Sites with built structures are small, level, and compact. The hard surfaced sites are typically larger than those dominated by structures, have level topography, and can be irregular in shape. All of these sites have extensive impervious surface cover, with tier 3 clusters visually differentiated by the presence of commercial/industrial units and/or vegetation. The built with vegetation group comprises sites dominated by structures and/or hard surfaces, but with a significant proportion of vegetation, often located along site boundaries. Landscape metrics are variable across the group, reflecting prior land use and informing the tier 3 clustering.

The predominantly pervious sites are differentiated based on a combination of vegetation type, successional stage, and distinct landscape metrics, with tier two groups identifying vacant sites with successional vegetation, those with predominantly short vegetation, and highly vegetated sites. The vacant with successional vegetation sites are of varying size, and can be uneven and irregularly shaped. These sites demonstrate evidence of previous man-made structures or materials existing alongside pioneer vegetation. Sites with predominantly short vegetation are generally larger than impervious types, may have some uneven topography, and while typically regular in shape, can be irregular. These sites have extensive pervious surface cover dominated by grassland areas. Tier 3 clusters reflect differences in the relative proportion of hard surfaces and canopy cover. The highly vegetated sites tend to have a moderate area, uneven topography, and an irregular shape, with a high proportion of tree canopy cover. At tier 3, clusters are distinguished by land cover.

In addition to the tier 2 groups described above, a number of distinct brownfield types were identified in the first and second applications of the clustering algorithm (see Methods and Fig. 4). These include sites with extensive hectarage (types *(f)*, *(v)* and *(z)*), those with a comparatively irregular shape (type *(p)*), sites containing water bodies (types *(g)*, *(r)*, and *(w)*), and those dominated by bare earth (type *(q)*).

The predominantly impervious built with vegetation group (types *(h)* to *(l)*) and the predominantly impervious vacant with successional vegetation group (types *(m)* to *(o)*) display evidence of dereliction and early successional transition. This emphasises the transient nature of the typology where impervious sites, if left undeveloped, over long periods of time, can transition from dominantly impervious to highly vegetated under specific surface conditions, especially where structures are demolished and hard surfaces disaggregated. It is also clear that brownfield sites that may potentially be more difficult or more costly to develop, such as sites with uneven topography (type *(o)*), irregular shapes (type *(p)*), and those containing a water body (types *(r)* and *(w)*), display superior levels of pervious and highly vegetated land cover.

3.3. *Distribution of brownfield typology across the urban environment*

The distribution of the primary brownfield groups highlights the dominance of predominantly impervious types in urban areas and predominantly pervious types in *peri*-urban areas, with a more balanced proportion of impervious and pervious types in suburban areas (Fig. 5).

Further examination of the distribution of the twenty-six brownfield types (typology tier 3) across the urban environment reveals four groups with divergent spatial patterning (Fig. 6 and Fig. 7). Within the predominantly impervious class, brownfield types *(a)* to *(g)*, with high percentages of artificial structures or surfaces (>70 % land cover), are typically clustered in urban areas and district centres, with very low occurrence in *peri*-urban areas. In comparison, types *(h)* to *(l)*, which contain moderate amounts of vegetation and bare earth, are less clustered in urban centres and more distributed than the significantly impervious types. The majority of the predominantly pervious class are more widely distributed still, with types (m) to (y) all occurring in urban areas, but with the majority of sites located in suburban and *peri*-urban areas of the conurbation. The exception to this is type (z), very large

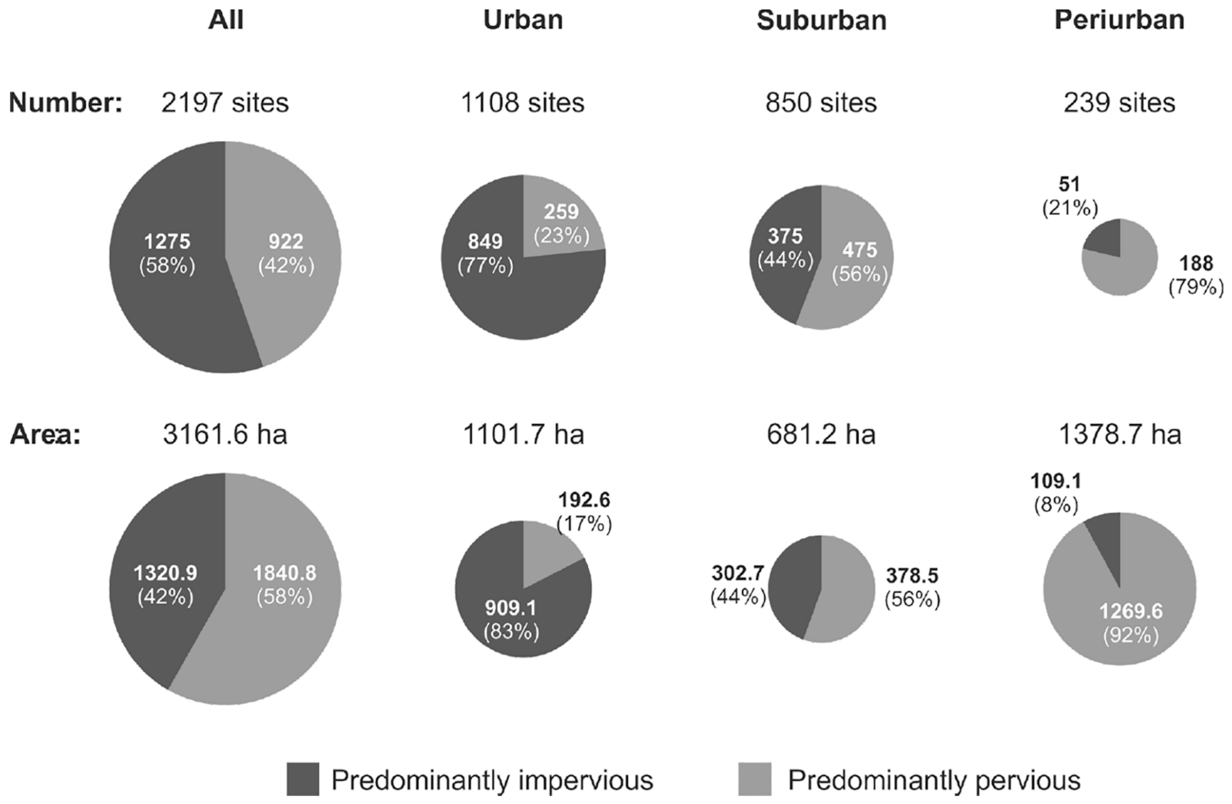

Fig. 5. Distribution of tier 1 of the hierarchical brownfield typology across the urban, suburban, and *peri*-urban zones. The area of the pie charts is proportional to the total number (top panel, based on classification of the centroid of each polygon) or area (bottom panel, based on area of each polygon within each zone) of the brownfield sites.

open green space, which occurs almost exclusively in *peri*-urban areas.

4. Discussion

Brownfield in Greater Manchester is unequally distributed and largely concentrated in built up urban areas, similar to many other post-industrial cities (De Sousa, 2003; Frantál et al., 2013; Longo & Campbell, 2017). Indeed, 50.43 % of brownfield sites are located within urban areas, 38.69 % suburban, and 10.88 % in *peri*-urban areas. While they are less numerous, *peri*-urban sites are much larger, and comprise 43.61 % of the total area of brownfield land, compared to 34.84 % urban and 21.55 % suburban. The relatively large area of *peri*-urban brownfield sites can be attributed to large scale activities at sites, such as historic mining or quarrying which usually require large areas (Grimski & Ferber, 2001).

Two key choices when evaluating brownfield re-use options are the consideration of residential/commercial redevelopment or renaturation; however, in view of a lack of appropriate guidelines (Banzhaf, Arndt, & Ladiges, 2018), the approach proposed here may aid the decision-making process. In planning practice, deciding whether brownfields should be redeveloped, greened, or left to natural succession, typologies may be of particular importance. For example, the landscape plan of the City of Dresden (Germany) under the "Leitbild" model proposes a compact city in an ecological network, and recommends the development of brownfield sites according to location in the urban fabric to ensure a compact city incorporating a green network, within which the concepts of green infrastructure and ecosystem service could support planning practice (Artmann, Bastian, & Grunewald, 2017).

The novel three-tier hierarchical typology identified twenty-six brownfield types distinguished by their land cover characteristics and landscape metrics. The typology's hierarchical organisation enabled granularity with different brownfield types to be either grouped at a higher level or dis-aggregated further in a logical way, conditional on the land cover and landscape metrics that define them. This method is flexible to allow further clustering of tier three types into subtypes if/where necessary and has wide applicability to classify brownfield in other post-industrial cities. Furthermore, the hierarchical classification using k-means clustering provides an statistical approach to identifying brownfield types based upon site-based physical and ecological characteristics, which makes it useful for a wide range of objectives.

The brownfield types identified vary in the proportion of impervious and pervious land cover as well as vegetation type and succession, where many brownfield types are significantly vegetated. In fact, the findings demonstrate that over half (51.25 %) of brownfield land is vegetated and pervious (comprising 27 % trees and shrubs, 24 % grass and herbaceous vegetation, 6 % bare earth, 1 % water), a total area of 1620 ha, which has previously been unaccounted for in green audits and green infrastructure maps used in policy and practice (Greater Manchester Combined Authority, 2019; The Environment Partnership, 2010). While few other studies report the proportion of different land cover types or green space on brownfield sites, in New York City, surveyed vacant lots were estimated to be 78 % vegetated and pervious (24 % coarse vegetation, 38 % fine vegetation, 15 % bare soil, 1 % water) (Kremer et al., 2013). The highly vegetated and pervious state of several brownfield types supports existing evidence that brownfield is a valuable component of urban green infrastructure, providing many ecosystem services (Mathey et al., 2015; Schadek et al., 2009), often to a greater extent than conventionally valued urban green spaces (Robinson & Lundholm, 2012).

The typology distinguishes large, topographically challenging, and irregularly shaped sites. These sites are often highly vegetated and have likely proven difficult to redevelop or access (Pagano & Bowman, 2004), allowing natural succession to take hold, often maturing into urban

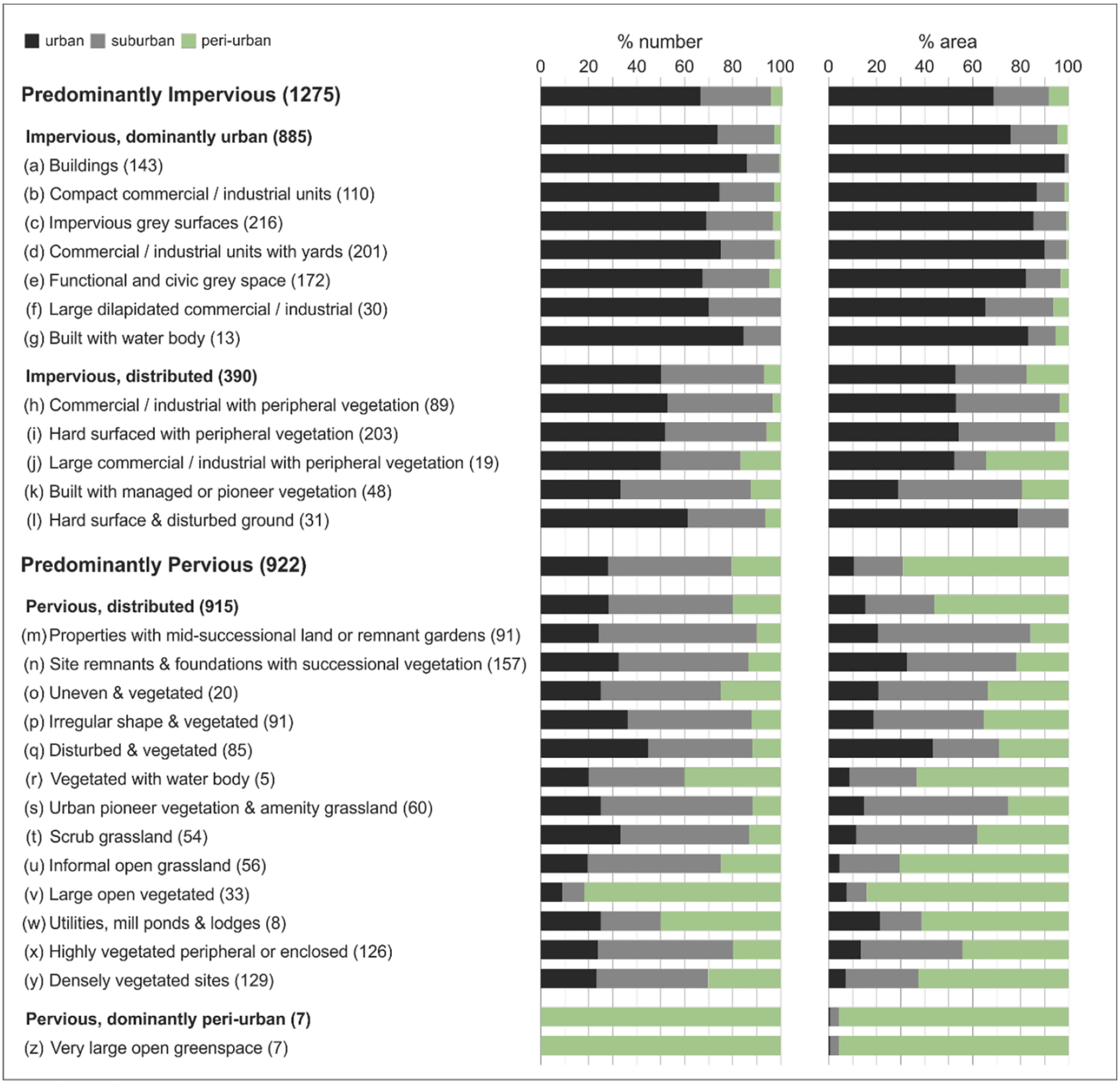

Fig. 6. Distribution of tier 3 of the hierarchical brownfield typology across the urban, suburban, and *peri*-urban zones by % number (based on classification of the centroid of each polygon) and % area (based on area of each polygon within each zone). Number of brownfields in parentheses.

woodland (Gilbert, 1995). Such sites, with limited or more costly development potential, are identified in the typology as highly vegetated. This information could also provide an initial indication of sites suitable for alternative use opportunities (Healey-Brown, Jackson, & Wray, 2011), such as greenways or pocket parks (Kremer et al., 2013), at a city-scale, which may also highlight their potential for providing connectivity, cultural ecosystem services, and human health and well-being benefits where most needed.

The typology revealed valuable detail regarding the distribution patterns of specific brownfield types across the city-region, which have been little researched. Brownfield types with a greater proportion of buildings and impervious surfaces are much more prevalent in densely built-up areas, whilst highly vegetated types are less clustered and more evenly distributed across urban, suburban, and *peri*-urban areas. This contributes valuable knowledge about the distribution of green infrastructure to enhance socio-ecological resilience, which is especially important at the city scale (Meerow & Newell, 2017).

In this respect, the findings emphasise the potential contribution of predominantly pervious brownfield types (types (m) to (y)) to urban ecosystem services and green infrastructure. These types are primarily present in built-up urban areas (some containing a high proportion of canopy cover e.g., type (y), (o), and (p)), and widely distributed across the conurbation. Brownfields in urban locations are a principal target for redevelopment, and whilst they are often surveyed for protected habitats and species pre-development, regulating ecosystem service provision by these areas is not considered. Thus, in the absence of priority habitats, highly vegetated or pervious brownfields providing regulating ecosystem services are likely being lost undetected.

This is important given the inequalities in open and green spaces in urban areas (Mitchell & Popham, 2007; Schüle, Gabriel, & Bolte, 2017), and highlights the potential contribution of brownfield vegetation to supporting urban resilience (Meerow & Newell, 2019). In cities undergoing urbanisation and significant modifications to land use and land cover (often closely linked with major urban planning policies and

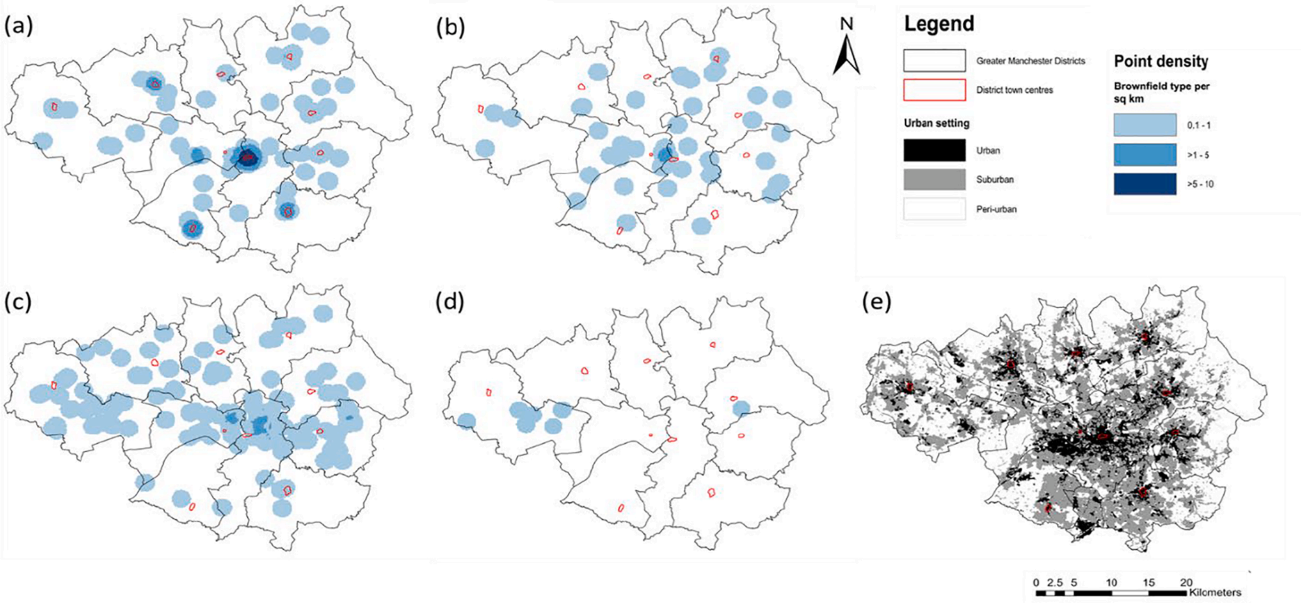

Fig. 7. Examples of divergent spatial patterning observed within the typology. (a) Impervious and dominantly urban sites, represented by type *(a) buildings*, (b) Impervious and distributed sites, represented by type *(k) built with managed or pioneer vegetation*, (c) Pervious and distributed sites, represented by type *(y) densely vegetated*, and (d) Pervious and dominantly *peri*-urban sites, comprising type *(z) very large open green space*, (e) Urban, suburban and *peri*-urban zones in Greater Manchester. Base maps are © Crown Copyright/database right (2021). Urban zones from reclassified land cover map 2015 (Rowland et al., 2017) © NERC (CEH) EDINA Digimap Ordnance Survey Service. Town centres from (Ministry of Housing Communities and Local Government, 2016) no conditions apply. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

brownfield redevelopment), the study of environmental implications for *at-risk* communities is becoming progressively important (Jennings, Johnson Gaither, & Gragg, 2012; Rufat, Tate, Emrich, & Antolini, 2019). However, the consideration of brownfield redevelopment rarely considers the unequal access to green space in socially vulnerable areas (Haaland & van Den Bosch, 2015; Mitchell & Popham, 2007). That said, Koch, Bilke, Helbig, and Schlink (2018) found that with smart urban planning approaches, and incorporating green space into brownfield redevelopment plans, brownfield redevelopment does not necessarily result in negative ecosystem service impacts. However, research integrating brownfield ecosystem service indicators or models into brownfield redevelopment evaluation is an emerging field (Kolosz, Athanasiadis, Cadisch, Dawson, Giupponi, Honzák, Martinez-Lopez, Marvuglia, Mojtahed, & Ogutu, 2018), and is lacking consideration of different types of brownfields present at a city-scale. This imparts the usefulness of the typology for careful strategic selection for redevelopment, greening, or interim use of brownfield based on their characteristics and location, particularly where there is a current lack of open or green space. The redevelopment of highly vegetated brownfield types identified in the typology would impact upon any socio-ecological benefits provided by the natural/semi-natural land cover components present on predominantly pervious types, and conversely, the approach used here could identify those that may benefit from some green intervention, or indeed prove difficult to develop.

Other brownfield mapping approaches have aimed to identify brownfield in the absence of land use databases (Hayek, Novak, Arku, & Gilliland, 2010; Xu & Ehlers, 2022), provide information about current land use (Kremer et al., 2013), future land use possibilities (Abdullahi & Pradhan, 2016), and identifying where existing green networks intersect with brownfield to examine ecological connectivity (Brun & Pietro, 2021). It must be noted that many examining vacant lots in the U.S, as opposed to previously developed brownfield, include previously undeveloped land which is not at risk of development (Kim et al., 2018; McPhearson, Kremer, & Hamstead, 2013). Furthermore, several approaches analyse a sample population of brownfields, and mapping the total stock of brownfield at a regional scale, which identifies land cover and landscape metrics at an individual site level, is lacking. The remote sensing method presented here has limitations and does not include data for contamination, hazards, land ownership or physical barriers. However, these, and existing and new data derived from other mapping approaches, once available, can be added to the pre-existing GIS data of individual brownfields and examined within the typology to emphasise patterns and provide a more comprehensive database in the future.

The brownfield database and typology have several valuable applications for urban planning for a variety of stakeholders including local authorities, developers, and community groups. Firstly, the typology could be used to inform strategic sustainable redevelopment, by identifying trade-offs between sites with different physical and ecological characteristics for redevelopment or green remediation measures. For example, a highly vegetated site may offer potential benefits to urban areas with an increased risk of exposure to environmental hazards, whereas the redevelopment of a highly impervious and less productive site may not result in the same adverse impacts on urban resilience. Alternatively, if there is a dearth of green space in the neighbourhood of such a highly impervious site, it could be targeted for strategic greening to aid urban resilience. Secondly, the typology may be useful for initial site investigation to identify constraints or hindrances to redevelopment (e.g., dense vegetation, water bodies, steep topography, built structures that require demolition or surface breakup work). Thirdly, the typology could be used to identify brownfield sites that may be suitable for temporary open space uses. Several brownfield types, including type (c) impervious grey surfaces, (i) hard surfaced with peripheral vegetation, and (u) informal open grassland, would require relatively little work to be put into productive use (Rall & Haase, 2011). These types of sites, if not earmarked for immediate development, offer prime opportunities for temporary uses, such as recreational space or urban agriculture, which can positively benefit the local community (Mathey et al., 2015). Fourthly, the typology could be used to indicate habitats on brownfield. For example, bare earth, which was identified on many brownfield types (and a defining characteristic of types (l) and (q)), could inform the identification of Open Mosaic Habitat. Characterised by a mosaic of bare earth, herbaceous and scrub vegetation, and pools (Lush, Shepherd, Harvey, Lush, & Griffiths, 2013), Open Mosaic Habitat is recognised for its high environmental value and is a Priority habitat on the UK Biodiversity Action Plan.

The brownfield typology developed here provides a valuable tool to understand the physical and ecosystem service characteristics of brownfield and their distribution at city-scale. The remote assessment, whilst useful for enabling analysis of all brownfields across a city-region, presents only a snapshot at the time the aerial imagery was taken. The nature and rate of redevelopment, or indeed natural succession, may mean that some brownfield sites contain different physical and ecological characteristics, though the transitional and cyclical nature of brownfield abandonment, natural succession, management, and redevelopment mean the typology is still a relevant tool. Employing the typology using a temporal approach, utilising historical and/or future data, may provide valuable insight into the life cycle of brownfields to inform strategic planning, urban resilience, or maintenance routines. For example, how end-of use condition or land management impacts upon the establishment and development of vegetation structure. Alternatively, temporal urban brownfield change is relatively unstudied in a socio-ecological context (Kattwinkel, Biedermann, & Kleyer, 2011), and could inform about potential interim ecosystem services benefits to local communities. The method used to create the brownfield typology is transferable to other locations or land use types. For example, should the method be used in other locations or even for different land use types (e.g., parks), once the land parcels of interest are identified, and digitised (if data is not available), the variables used to create the typology are measurable for any land parcel e.g., land cover, size, shape, and slope. The statistical analysis techniques used are widely available within many statistics packages.

5. Conclusion

This research developed a novel brownfield typology using hierarchical classification (k-means clustering), incorporating several physical characteristics of brownfield land, which can be used for a range of objectives and is widely applicable to other post-industrial cities. Application of the typology to the case study of Greater Manchester, UK, revealed interesting insight into the spatial distribution and diversity of the twenty-six distinct types of brownfield identified within the city-region. Results highlighted the significant 'hidden' green space present on brownfield, which whilst unaccounted for in green infrastructure maps used in practice, arguably contributes positively to the wider green infrastructure network. Brownfield land is thus a valuable dynamic resource in post-industrial cities and redevelopment should be planned at the city-scale to ensure careful strategic selection of sites for redevelopment, greening, or interim use based upon their characteristics and location, as supported by the typology presented here together with socio-economic and risk factors. This is essential to make evidence-based decisions and ensure the best strategic use of brownfield to aid urban resilience.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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