The potential contribution of brownfield ecosystem services to urban resilience

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The potential contribution of brownfield ecosystem services to urban resilience

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“That Nature ne'er deserts the wise and pure.

No plot so narrow, be but Nature there,

No waste so vacant, but may well employ

Each faculty of sense, and keep the heart

Awake to Love and Beauty!”

S T Coleridge, 1797

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Abstract

Urbanisation processes result in land cover changes which can modify the biological, chemical, and geological characteristics of the urban environment. As a result, cities face increased exposure to environmental hazards, placing individuals and communities at risk. While the role of urban green space in mitigating these hazards and enhancing urban resilience is widely recognised, brownfield land has been largely overlooked, with a paucity of research investigating the contribution of brownfield ecosystem services to urban resilience. Brownfield land is experiencing rapid land cover changes in urban areas due to brownfield-first approaches to development. Brownfield is disproportionately located in densely built urban areas, characterised by high levels of socio-economic deprivation, low amounts of green space, and increased exposure to environmental hazards. As the developmental pressure on brownfield increases, and the importance of urban resilience intensifies, it is important to understand the potential impacts of brownfield loss before they are redeveloped. It is important to understand the potential impacts of urban redevelopment processes utilising brownfield before they are redeveloped. Thus, this research explored how brownfield ecosystem services may contribute to building resilience to environmental hazards in urban areas. This research applies new approaches to the characterisation of brownfield, the quantification of their ecosystem services, comparison to existing green infrastructure, their relationship to environmental hazards and those who are most at risk in Greater Manchester, UK.

Findings show that brownfield is widely distributed, disproportionately concentrated in urban areas, providing highly vegetated (51%) and pervious (58%) space. A novel typology developed utilising land cover analysis, landscape metric analysis and cluster analysis identified 26 distinct types which vary in terms of physical and ecological characteristics and impacts upon ecosystem services provision. In total, brownfield provided an estimated 52 kt of carbon storage, annual carbon sequestration of 2kt, removed 305t of air pollution, and avoided 133,000m^3 of surface water runoff. Several types of brownfield (irregular shaped and vegetated, densely vegetated, vegetated with water body, and uneven and vegetated), provide more regulating ecosystem services than many types of park. In densely built urban areas, brownfield provides five times more regulating ecosystem services than parks, where scenario analysis indicated that interventions like extensive tree planting could deliver an 8-fold increase in benefits. Hotspots where high social vulnerability and exposure to environmental hazards intersected with increased brownfield were identified in urban regions. Brownfield is 8 times more prevalent in acute socially vulnerable areas than areas of low social vulnerability. Recommendations for strategic greening opportunities, the removal of impervious surfaces, enabling public access and redevelopment avoidance are made.

The findings demonstrate several types of brownfield can provide significant regulating ecosystem services, are a valuable component of a city's green infrastructure in densely built urban areas and have scope to be managed or modified to maintain or increase urban resilience. The abundance of brownfield, with both high and low ecosystem service provision, in socially vulnerable neighbourhoods, suggest that brownfield could provide additional open green space and reduce exposure to environmental hazards. Strategic redevelopment of brownfield should be employed contingent on their location, distribution, and characteristics, and it is recommended that a rapid ecosystem service assessment tool is developed to support practice.

Declaration

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute of learning.

Name in block capitals: PAUL DAVID PRESTON

Signed: __ ____

Date: ___ ____

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Acronyms/abbreviations

Reference	*Description*
AWMSI	Area Weighted Mean Shape Index
BiLISA	Bivariate Local Indicator of Spatial Association
CPRE	Campaign to Protect Rural England
DEFRA	Department of Environment, Food and Rural Affairs
GHG	Green House Gas
GIS	Geographic Information Systems
IMD	Indices of Multiple Deprivation
IPCC	Intergovernmental Panel on Climate Change
LCM	Land Cover Map
LISA	Local Indicator of Spatial Association
LSOA	Lower Super Output Area
MEA	Millennium Ecosystem Assessment
MPFD	Mean Patch Fractal Dimension
NLUD-PDL	National Land Use Database of Previously Developed Land
OMH	Open Mosaic Habitat
ONS	Office of National Statistics
OS	Ordnance Survey
PAR	Perimeter-Area Ratio
PCA	Principal Component Analysis
PM	Particulate Matter
SUDS	Sustainable Urban Drainage Solution
UHI	Urban Heat Island

Chapter 1: Introduction

Cities are dynamic systems in which size, form, ecology, socio-economic structure, political trends, and technology continuously evolve (Hall, 2006; Kennedy, Cuddihy, & Engel-Yan, 2007). In the global North, the latter half of the twentieth century has been characterised by urban industrial decline and increased land abandonment in cities arising from changes to industrial processes and improvements in technology and infrastructure (Gorman, 2003; Hall, 2006). Simultaneously, business and industry were encouraged to pursue cheaper, more accessible greenfield land (previously undeveloped land in rural areas, used for agriculture or left to grow naturally) at the edges of the city (Gorman, 2003; Kennedy et al., 2007). These dynamics of urban land abandonment and changes in urban form left behind previously developed plots of land exhibiting a multitude of forms, now termed brownfield land in the UK. The term brownfield land (previously developed land that lies vacant or derelict and requires intervention to return the land into productive use) is generally juxtaposed against greenfield (Hollander, Kirkwood, & Gold, 2010).

Urbanisation, the growth of cities to accommodate the influx of people, is rapidly increasing, and a greater proportion of the world's population now reside in cities compared to rural areas (Antrop, 2004; United Nations, 2019). The realisation that expansion of urban areas into rural areas was not sustainable, and that denser urban settlements are less environmentally challenging, has led to regulation to prevent urban sprawl and an increase in urban re-densification (United Nations, 2019). Urbanisation, whether through urban sprawl or densification, often results in land use and land cover changes, frequently with the replacement of pervious and vegetated land with artificial and impervious structures and surface materials (Bibby, 2009). Over the past few decades, a requirement to adopt sustainable land use strategies in the UK has led to a focus on the regeneration of urban brownfield for residential and commercial purposes to reduce greenfield development (Department for Communities and Local Government, 2017b; Oliver, Ferber, Grimski, Millar, & Nathanail, 2005).

Increasing urbanisation and densification presents many social challenges including social inequity, poverty, and unequal access to goods, services, opportunities, and resources (UN-Habitat, 2020). Likewise, cities and their residents are increasingly facing a range of interrelated environmental challenges including climate change impacts, land use change, biodiversity loss, consumption of energy and resources, greenhouse gas emissions, flooding, pollution, and environmental inequity (UN-Habitat, 2020). Exposure to urban environmental hazards including air pollution, flooding and the urban heat island effect (UHI) impacts upon human health and wellbeing (Cutter, Boruff, & Shirley, 2003; McMichael et al., 2003; Wilby, 2007). These hazards are likely to be exacerbated by future changes in climate (IPCC, 2007; Wilby, 2007) and modifications to urban land (Oke, 2002), where the most vulnerable individuals and communities have been associated with built up urban areas (Cutter et al., 2003; Kaźmierczak & Cavan, 2011). Improving urban resilience to these challenges, to protect cities and their residents against climate and environmental hazards, whilst safeguarding the vulnerable, is a central component of environmental action plans around the World (Defra, 2018; European Commission, 2013; UN-Habitat, 2020).

Resilience is a key aspect of sustainable development and resource consumption (Adger, 2000). In terms of planning responses to natural or anthropogenic urban environmental challenges, nature-based solutions, primarily the installation of green infrastructure, are increasingly seen as key to enhance urban resilience as populations increase (Meerow, Newell, & Stults, 2016; Pickett, McGrath, Cadenasso, & Felson, 2014; Schäffler & Swilling, 2013). This reflects wide recognition of the multitude of benefits provided by green infrastructure, including protecting ecosystem state and biodiversity, protecting ecosystem functioning and promoting ecosystem services, promoting the health and well-being of society, and supporting a green economy and sustainable development (European Commission, 2012). Existing green infrastructure is, however, unevenly distributed across cities and largely concentrated in wealthier areas (Jennings, Johnson Gaither, & Gragg, 2012; Mitchell & Popham, 2007; Mitchell & Popham, 2008; Schüle, Gabriel, & Bolte, 2017b; Sister, Wolch, & Wilson, 2010; Wolch, Byrne, & Newell, 2014). Furthermore, in the current drive for urban densification, green space can be lost, and land available for new green space, and its associated benefits, is lacking (Haaland & van Den Bosch, 2015). Thus, additional urban green infrastructure would require adequate urban land and/or innovative design (Haaland & van Den Bosch, 2015).

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). Over the last decade, research has shown that many urban brownfields can contain vegetation, water and bare earth, which can provide many ecosystem services (Francis & Chadwick, 2013; Mathey, Rößler, Banse, Lehmann, & Bräuer, 2015), contribute to urban biodiversity (Bonthoux, Brun, Di Pietro, & Greulich, 2014), and be of public value as open amenity space (Kamvasinou, 2011; Rall & Haase, 2011). However, in many cities, urban densification including redevelopment of brownfield sites has resulted in rapid and extensive land use and land cover changes, thereby altering urban structure with potentially significant impacts on the wider urban environment as the aforementioned benefits are lost (Oke, 2002; Schulze Bäing & Wong, 2012). To improve urban resilience in response to social and environmental challenges and ensure sustainable land use strategies (Chen et al., 2009), it is therefore imperative to understand more about brownfield land, and specifically, to be aware of both their current and future potential in delivering urban ecosystem services. If this is not established before redevelopment, it may result in maladaptation with a negative impact upon urban resilience.

1.1 Information needs for policy and practice and research gaps

Brownfield is increasingly undergoing redevelopment and regeneration in urban areas in a drive for sustainable urbanisation. Simultaneously, research is emerging showing that brownfield may provide socio-ecological benefits and opportunities which may be lost without sufficient information supply. To ensure the best use of brownfield today and in the future, several information needs for policy are required; **(i)** comprehensive *up-to-date* brownfield databases (reliant on standardised reporting mechanisms), **(ii)** a better understanding of the specific physical characteristics of brownfields, **(iii)** how brownfields currently perform in terms of ecosystem services, and their future potential, and **(iv)** to understand their environmental context, and how they relate to socio-ecological factors in urban systems. This information is important to identify opportunities to enable a strategic and well-informed land allocation in future.

Whilst there is some existing research that seeks to understand urban brownfield land and its potential to contribute to urban resilience (Mathey et al., 2015), there remain several research gaps. **First**, much existing literature fails to examine the extent and distribution of brownfield at the city scale and investigates individual case study sites. Brownfield databases are deficient, and gaps exist in current knowledge regarding the complete stock of brownfield. A comprehensive database is essential for the identification and assessment of brownfield to gain a complete picture of the extent, distribution, and number of brownfields in a city. Some current brownfield databases only include brownfield that is available for redevelopment within a specific timeframe, or suitable for a minimum number of homes, leading to incomplete databases for research purposes. There has also been some uncertainty surrounding the number of brownfield sites due to the low level of response from reporting bodies (Coffin, 2003).

Second, there is a paucity of research focusing on the specific physical structure and character of brownfields, and a classification of brownfield which can be applied in a socio-ecological context is currently lacking. The suitability or priority of brownfield for redevelopment, based on remediation time and financial or economic factors, has been identified, but potential positive attributes are rarely acknowledged (Alker, Barrett, Clayton, & Jones, 2000b; Dasgupta & Tam, 2009). Brownfields are often misrepresented as a single entity, or included in broad umbrella categories of brownfield, such as vacant, industrial, or commercial. Furthermore, these approaches often lead to negative perceptions of brownfields as low importance spaces that negatively impact upon urban communities (Kim, 2016). This brings with it the risk of uninformed, disproportionate, and extensive redevelopment of brownfields sites. Such approaches do not fully address the diverse nature of brownfields in terms of land cover, land use, ecosystem services, or urban environmental context (Kim, Miller, & Nowak, 2018; Rupprecht & Byrne, 2014).

Third, quantification of regulating ecosystem service provision by brownfield sites are lacking. It is important to understand the value of brownfield to support ecosystem service monitoring, planning and management, and support strategic redevelopment to prevent loss of ecosystem services in urban areas. Brownfield ecosystem service research has primarily focussed on site scale recreational and cultural services (Mathey et al., 2015; Pueffel, Haase, & Priess, 2018), and biodiversity (Angold et al., 2006; Bonthoux et al., 2014; Shaw, 2011), and less so on regulating ecosystem services. Furthermore, those studies which have examined regulating ecosystem services have focused on impacts on local microclimate (Koch, Bilke, Helbig, & Schlink, 2018; Mathey et al., 2015), with no studies examining the dynamics of flood water attenuation and air pollution for all brownfields at a city scale.

Fourth, little research has explored how brownfield currently, or could potentially, contribute to existing urban green infrastructure and ecosystem benefits. Current research into the effectiveness of green infrastructure for urban adaptation and resilience has focussed on conventional green spaces such as; parks, woodland, green roofs, riparian systems, street trees and gardens (Benedict & McMahon, 2002; Bolund & Hunhammar, 1999; Gill, Handley, Ennos, & Pauleit, 2007; Tzoulas et al., 2007; Woch, Kapusta, & Stefanowicz, 2016). Furthermore, there has been no direct comparison of brownfield to existing green infrastructure in terms of urban distribution and contribution to ecosystem service provision. It is critical to understand this contribution as while the drive to install additional green infrastructure in cities is intensifying, the synchronous loss of brownfield vegetation may result in unintentional net losses. This information may also inform targeted urban greening for brownfields located in areas where there is inequity in existing green infrastructure and ecosystem service provision.

Fifth, the spatial dependency between brownfield and *at-risk* communities from a socio-ecological perspective is not understood and is not adequately addressed by the current body of literature. Research has previously considered brownfield as a hazard to *at-risk* communities (Bambra et al., 2015; Carroll & Kanarek, 2018; Eckerd & Keeler, 2012). However, in cities undergoing urbanisation, and significant modifications to land use and land cover (often closely linked with major urban planning policies, and brownfield redevelopment), the study of environmental implications for *at-risk* communities is becoming progressively important (Jennings et al., 2012; Rufat, Tate, Emrich, & Antolini, 2019). Identifying spatial interactions between brownfields and *at-risk* communities from a socio-ecological perspective is important to better understand the potential positive or negative consequences of urban redevelopment processes. Identifying strategic redevelopment or modification opportunities for brownfields that may potentially benefit *at-risk* communities through hazard alleviation, planning adaptation and resilience actions in urban areas. To the authors best knowledge there is currently no approach for making these recommendations for brownfields at a city-scale.

1.2 Thesis aim and objectives

The principal aim of this research was to explore how brownfield ecosystem services may contribute to building resilience to environmental hazards in urban areas. To achieve this research aim, the specific objectives were:

> **Objective 1**: To characterise brownfield land, including consideration of spatial land use and land cover characteristics, and its distribution across the urban environment (**Chapter 3**).
>
> **Objective 2**: To assess the current provision of regulating ecosystem services of brownfield land, the potential if greened, and compare to existing urban green infrastructure (**Chapter 4**).
>
> **Objective 3**: To investigate the spatial dependency between brownfield and *at-risk* communities and make recommendations for the most effective use of brownfield land to enhance urban resilience (**Chapter 5**).

1.3 Study area: Greater Manchester

Greater Manchester in the North West of England, UK, is an extensive metropolitan area (1276 km^2) encompassing ten local authorities with a population of 2.8 million residents (GMCA, 2018) (Figure 1.1). A polycentric conurbation, the cities of Manchester and Salford form the urban core, with other urban centres distributed across the city region (GMCA, 2018). 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). The ten district councils (Fig. 1.1) and Mayor govern the region as the Greater Manchester Combined Authority (Greater Manchester Combined Authority, 2018), working together with a Local Enterprise Partnership (LEP) which plays a central role in deciding local economic priorities (Greater Manchester Local Enterprise Network, 2021).

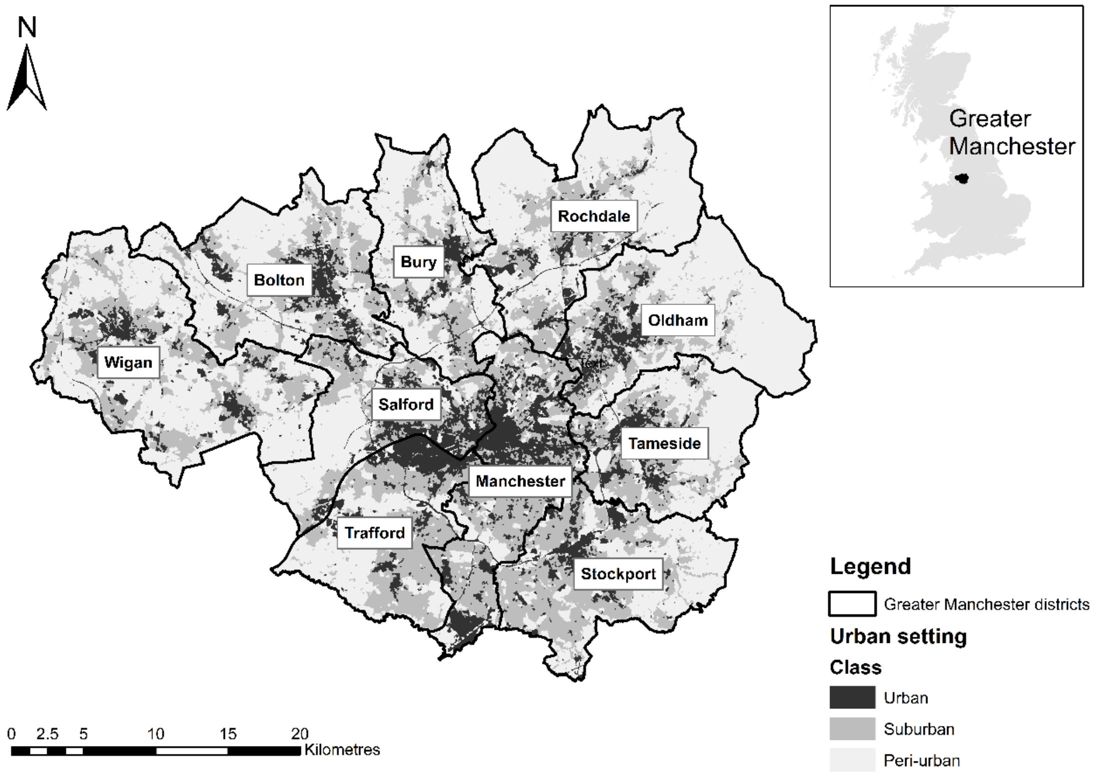


Figure 1.1: Greater Manchester. GB base map is © Crown Copyright/database right (2021). An Ordnance Survey/EDINA supplied service. Greater Manchester district boundary data, ONS (2018). Urban setting classes based on Land Cover Map 2015 by Rowland et al. (2015)

Greater Manchester's prolific industrial past has left a legacy of many brownfield sites widely distributed across the conurbation (Barlow, 1995). What is significant to the brownfield phenomena in the region is the pattern of industry in each satellite town or district (Barlow, 1995), which has led to the emergence of brownfield sites spread across the conurbation with clustering around each separate urban centre, rather than being centralised regionally (Dixon, 2007). The Greater Manchester Spatial Framework (GMSF) (Greater Manchester Combined Authority, 2019c), identifies urban sites for residential and commercial developments, many of which are brownfield. The GMSF has a strong focus on brownfield-first for residential development in Greater Manchester, to reduce the use of greenfield and green belt land, and address areas of dilapidation and poor land use (Greater Manchester Combined Authority, 2019c).

Demographics and socio-economic status varies across the Greater Manchester conurbation (Lindley et al., 2011). After Greater London and the West Midlands, Greater Manchester is the third most populous conurbation in the United Kingdom (ONS, 2020), and is increasing in size, growing 7.7% between 2006 and 2016 (Greater Manchester Combined Authority, 2017), and estimated to increase by another 190,000 residents by 2037, inevitably increasing the requirement for new homes (Greater Manchester Combined Authority, 2019b). In addition, Greater Manchester is estimated to be the third most deprived conurbation in England, with more than 11% of its neighbourhoods (Lower Super Output Areas (LSOA)) amongst the 5% most deprived neighbourhoods in England, and a quarter of dependants under 20 year olds living in poverty (Greater Manchester Combined Authority, 2017).

Across the conurbation rainfall and temperature can vary significantly topographically and geographically (Cavan, 2010). Greater Manchester has an annual average rainfall of 1068mm (Cavan, 2010), with January averaging 103.55mm and July 71.45mm (1971 – 2000). In terms of climate, Greater Manchester has an average temperature of 9.21°C (1971-2000) (Carter et al., 2015; Cavan, 2010). Average daily minimum temperatures range between 1.15°C (January) to 11.86°C (July), whilst average daily maximum temperatures range between 6.2°C (January) and 19.75°C (July) (1971 – 2000) (Carter et al., 2015; Cavan, 2010).

Flooding in Greater Manchester is a major concern and the region is exposed to one of the highest risks in England with over 55,000 properties at risk (GM Resilience, 2021). The River Mersey and River Irwell have a significant impact on the risk of river flooding, with 89 historic flood events documented in the last 150 years (Brisley, Williamson, & Lloyd-Randall, 2018). Furthermore, the incidence of surface water flooding is increasing (Carter et al., 2015), and an estimated 127,700 people are at risk of pluvial flooding in the region, based on the latest census data for population in built-up areas (ONS, 2020). Carbon emissions in Greater Manchester (2018) were estimated to be 10MtCO_2e of which industry and commercial account for 35%, domestic 39%, and transport 26% (Greater Manchester Combined Authority, 2019a). It should also be noted that land use also plays and important role GHG cycles and land-based emissions are now included in GHG accounting (Harper et al., 2018). Pollution monitoring for 2016, reveals that air pollutant exceedance levels (>200µg per m^3) of NO_2 were surpassed 90 times (Oxford Road station) (Cox & Goggins, 2018), and of PM_{10} (>50µg per m^3), 42 times (Greater Manchester Combined Authority, 2017). Greater Manchester has set out several plans and strategies to reduce air pollution and carbon emissions in the conurbation (Clean Air Greater Manchester, 2020; Cox & Goggins, 2018), and also to reduce the risk and manage the impacts of flooding (Brisley et al., 2018; Greater Manchester Combined Authority, 2019a).

1.4 Thesis structure

This chapter introduced the background, information needs for policy and practice, gaps in the current research, and the principal research aim and objectives, and study area. The individual chapters of this thesis are structured in the following way:

- **Chapter 2** critically reviews the literature which is the foundation for this research. This includes an examination of the key themes in this research; **(i)** urban challenges, including urban densification, environmental hazards, social vulnerability, environmental injustice; **(ii)** resilience approaches, an overview of green infrastructure, and ecosystem services; **(iii)** brownfield characteristics, benefits, opportunities, and **(iv)** challenges faced in addressing the gaps in the research regarding discrepancies in brownfield designation, identification, and classification.
- **Chapter 3** identifies and comprehensively characterises brownfield in order to create a novel and highly transferable brownfield typology. This addresses research **Objective 1** and forms the basis for research in the subsequent chapters allowing a consistent approach to classification to underlie this thesis.
- **Chapter 4** addresses research **Objective 2** and utilises ecosystem service modelling tools for both city scale and site scale case studies to investigate the current and potential future ecosystem service provision of brownfield. Applying the typology developed in **Chapter 3** and the creation of an urban park typology, this chapter makes an original and direct comparison between urban brownfield and park ecosystem services and establishes their distribution in urban areas. Scenario analysis is undertaken to investigate the potential of brownfield to contribute to urban resilience.
- **Chapter 5** addresses research **Objective 3** and investigates the spatial associations between brownfields, *at-risk* communities and exposure to environmental hazards using spatial and statistical analysis. The brownfield typology and indicators of ecosystem service provision are applied to establish the value of brownfield and make recommendations to maintain or enhance urban resilience.
- **Chapter 6** provides an overarching summary of the main findings and contribution to knowledge from the empirical research presented in **Chapters 3, 4 and 5**. A research critique and further lines of enquiry are presented, and implications for policy and practice are also discussed.

Chapter 2: Literature review

2.1 Introduction

Urbanisation presents several social, environmental, and economic challenges in modern cities (UN-Habitat, 2020). As pressures such as land use change, risk of environmental hazards, and environmental inequity increasingly affect cities and their residents, understanding the factors that can influence urban resilience becomes more important (UN-Habitat, 2020). It has also been established that the increasing urban population require the just distribution of environmental benefits (and burdens), including ecosystem service provision and access to green space (Sister et al., 2010). One widely adopted approach to increase urban resilience is the promotion of nature-based solutions and the introduction of green infrastructure to increase ecosystem service provision (Meerow & Newell, 2019). However, while recent research has identified some brownfield to be highly vegetated and beneficial to urban environments (Mathey et al., 2015), brownfield land is experiencing some of the greatest and most rapid land cover changes in post-industrial cities (Wong & Schulze Bäing, 2010). This has been driven by a brownfield-first redevelopment approach within 'sustainable urbanisation' strategies which seek to minimise development on greenbelt land at the edge of the city and limit urban sprawl (Longo & Campbell, 2017). Thus, while the purposeful installation of urban green infrastructure is increasing, many brownfield, potentially providing urban green infrastructure and ecosystem services, are being redeveloped (Mathey et al., 2015). This review focuses on four key themes: (i) urban challenges (Section 2.2), (ii) approaches to resilience (Section 2.3), (iii) brownfield characteristics, benefits, and opportunities (Section 2.4), and (iv) key research challenges relating to brownfields (Section 2.5). Section 2.6 concludes the review. These themes are discussed with a particular focus on the UK context.

2.2 Urban challenges

Over half of the world's population now reside in towns and cities (Antrop, 2004; United Nations, 2019). This proportion continues to grow, where it is projected that by 2050 68% of the global population will reside in urban areas (United Nations, 2019). Urban areas are rapidly expanding to accommodate this population growth (Dallimer et al., 2011). Urbanisation is a complex process which results in the modification of previously developed urban and undeveloped rural land into built-up areas and their associated land uses (Antrop, 2004). Increasing urbanisation presents several key challenges which are emphasised in the UN-Habitat (2020) World Cities Report. These include social inequity, poverty, unequal access to goods, services, opportunities, and several climate and environmental challenges (UN-Habitat, 2020). These climate and environmental challenges include the impacts of climate change, modification and change of urban land uses, the loss of biodiversity, increased energy and resources consumption, amplified emissions of Green House Gases (GHGs) and pollutants, and environmental inequity are key environmental issues in urban areas (UN-Habitat, 2020). The following subsections will provide an overview of urban challenges, including urban densification, environmental hazards (focussing on GHG emissions, air pollution and flooding), social vulnerability and environmental inequity.

2.2.1 Urban densification

The dynamics of urban growth has emerged as a key debate in sustainable urbanisation research, questioning whether urban areas should expand into the (surrounding) rural, undeveloped or agricultural areas (urban sprawl), or become more compact (urban densification) through the redevelopment of existing urban land (Dallimer et al., 2011). The balance between the sustainability, desirability and liveability of adopting urban sprawl or re-densification has been referred to as the compact city paradox (Artmann, Inostroza, & Fan, 2019; Neuman, 2005). Urban sprawl and densification have both been criticised due to negative impacts on social, economic, and environmental factors (Pauleit & Breuste, 2011), although urban sprawl has been considered more of a burden environmentally than dense urban settlements (Millennium Ecosystem Assessment, 2005).

Increasing populations, income growth, decreased transport costs, suburbanisation, and lower agricultural land prices are some of the factors thought to be instrumental in urban sprawl (Brueckner, 2000; Habibi & Asadi, 2011; Hall & Barrett, 2018; Nechyba & Walsh, 2004). In the twentieth century, low density suburban housing developments, and single use developments such as out of town retail outlets, not only provided new housing and amenities, but contributed to urban sprawl (Couch, Karecha, Nuissl, & Rink, 2005). This expansion of urban areas into the countryside eventually became restricted in the UK by the green belt policy (Hall & Barrett, 2018), which aims to prevent neighbouring towns merging into each other, safeguard the countryside and preserve the character of towns (Ministry of Housing Communities and Local Government, 2019b).

There is a housing shortage due to a variety of factors including: increasing urban populations, changes in urban demographics, income distribution, a lack of new housing stock, and financial deregulation. To meet housing demand and limit urban sprawl, numerous sustainable land use strategies for brownfields have been introduced including regenerating derelict and dilapidated areas and redeveloping vacant land (Schulze Bäing & Wong, 2012; Wong & Schulze Bäing, 2010). Additionally, post-industrial cities have shifted from mainly secondary industry sectors (e.g. manufacturing) to high levels of centrally located tertiary (retail) and quaternary

(IT) sectors, resulting in high demand for brownfield for residential and commercial properties in urban areas (Deng, Huang, Rozelle, & Uchida, 2008). This recent intensified interest in brownfield may result in continued urban re-densification in post-industrial cities (McFarlane, 2020). The Concerted Action on Brownfields and Economic Regeneration Network (CABERNET) identified a clear need to establish realistic and effective targets for the future regeneration of brownfield land across Europe (Oliver et al., 2005), and the US Environmental Protection Agency (US EPA) initiated the redevelopment of brownfield with the introduction of training and grants to redevelop contaminated land (the US definition of brownfield) (BenDor et al., 2011; Chen et al., 2009).

Indeed, over the past few decades, the redevelopment of brownfield has been argued to be the answer to the housing crisis in the UK (Campaign to Protect Rural England, 2018; Gabbatiss, 2019; Wong & Schulze Bäing, 2010). More recently in the UK, a 2017 Governmental white paper, named 'Fixing our broken housing market', set out plans to accelerate the development of derelict and underused brownfield land for residential purposes (Department for Communities and Local Government, 2017a). Lack of adequate or suitable housing in the UK is a long standing problem (Robertson, 2017), and the modern housing crisis has been characterised by growth in waiting lists for social housing, greater volume of short term letting, increased rents and house prices, higher levels of overcrowding, and decreasing housing quality (Robertson, 2017). Furthermore, many cities have witnessed rapid gentrification displacing the economically deprived (Newman & Wyly, 2006; Robertson, 2017). The cause of the current crisis is driven by wider political and economic factors including that populations have grown much more rapidly than the UK housing stock, exacerbated by the almost total cessation of local authority housing construction in the 1980s (Edwards, 2016; Mulheirn, 2019).

The protection of green belt land and the drive to redevelop brownfield sites for residential purposes is well supported by several national and local groups (Ganser & Williams, 2007), for example the Campaign to Protect Rural England (CPRE), argue that:

> *"brownfield land that is suitable for housing is a valuable resource because it provides an alternative to losing precious greenfield land to development. In turn, greenfield land can continue to provide many benefits in terms of fair access to green space near to where people live, space for nature and people, and mitigation of the climate emergency" (Campaign to Protect Rural England, 2020, p. 2).*

Ganser and Williams (2007) argue that political pressure from such groups was effective in highlighting the impacts of greenfield development including increased commuter times, loss of rural areas, and social segregation, leading to the UK government focussing on a brownfield-first approach to residential developments. The Department for Communities and Local Government (2017a, p. 14) state that a brownfield-first approach “will reduce speculative development, support villages, towns and cities, preserve the unique character of communities, and protect precious countryside”. Much research has also focussed on the benefits of urban brownfield redevelopment as a sustainable urbanisation solution (Bambra et al., 2015; Bambra et al., 2014; Dixon, Raco, Catney, & Lerner, 2008; Mert, 2019; Schädler, Morio, Bartke, Rohr-Zaenker, & Finkel, 2011).

Whilst it is clear that the regeneration of brownfield land can provide several social, economic and environmental advantages in urban areas (Chen, Hipel, Kilgour, & Zhu, 2009; Tang & Nathanail, 2012), the brownfield-first approach will inevitably lead to high density developments (Davies et al., 2011a; Dixon et al., 2008; Greater Manchester Combined Authority, 2019c). Housing density in England has been shown to be increasing, where brownfield redevelopment is more prevalent in low-income areas (Schulze Bäing & Wong, 2012). However, the UK National Ecosystem Assessment Technical Report (UK-NEATR) states that the escalation in housing density in urban areas is highly negatively correlated with open space availability and has stark environmental equity implications for urban areas (Davies et al., 2011a). The drive for brownfield-first redevelopment fails to consider the current or potential role that brownfield could play in terms of providing open space and ecosystem benefits, whilst the UK-NEATR emphasising the need for additional open space where housing density is high. There is a paucity of research examining brownfield as a potential contributor to urban green space and ecosystem service provision, which needs addressing in order for policy to consider this. Some brownfields may currently, or have the potential to, provide these functions in densely built urban areas which have little chance of receiving additional urban green spaces due to lack of space and value of land (Haaland & van Den Bosch, 2015; Mathey et al., 2015). Site visits undertaken during the completion of this thesis provides evidence that highly vegetated brownfields are currently being cleared and redeveloped (Fig. 2.1). Urbanisation and brownfield first policies emphasise the need to investigate how brownfield ecosystem services contribute to urban resilience before they are redeveloped and to understand the impacts of rapid brownfield land use / cover change on urban resilience.

Figure 2.1: Evidence of vegetation clearance on brownfield sites. (a) Aerial image of a brownfield site in Greater Manchester, which has remained vacant and densely vegetated since the 1990's. Image: (The GeoInformation Group, 2007). (b) Recent development is for residential buildings. Image: (Google Earth, 2019). (c) A highly vegetated Greater Manchester brownfield site very close to an urban centre. Image: (Author's image, 2018). (d) Now cleared of vegetation, the proposed uses include offices and leisure buildings. Images: (Author's image, 2019).

2.2.2 Environmental hazards

Urbanisation processes commonly involve increased industry, transport, construction, and the replacement of vegetated and pervious land cover with impervious and artificial surfaces (Oke, 2002; Seto, Sánchez-Rodríguez, & Fragkias, 2010). This changes urban structure, and land use function leading to alterations in surface-energy interactions and the biological, chemical, and geological characteristics of the urban environment (Foley et al., 2005; Oke, 2002; Seto, Güneralp, & Hutyra, 2012; Seto et al., 2010; Whitford, Ennos, & Handley, 2001). These factors have, for example, been linked to several key climate and environmental impacts (Douglas, 1983), including, decreased air quality (Mayer, 1999), increased greenhouse gases (GHG) (Foley et al., 2005), more frequent pluvial and fluvial flooding (Miller & Hutchins, 2017; Schreider, Smith, & Jakeman, 2000), and increased urban ambient air temperatures due to the urban heat island effect (UHI) (Oke, 1973). The following sections focus on air pollution, climate change and flood risk.

2.2.2.1 Air pollution

While the concentration of human endeavour in cities offers the potential for significant efficiency gains through economies of scale, it also concentrates energy use and associated emissions of greenhouse gases and air pollutants (Mayer, 1999). There are more than 3,000 anthropogenic air pollutants, and the impacts of many have not been investigated (Fenger, 1999). Air pollutants can generally be grouped into two main types; particulate matter (PM) are particles of dust or fluid suspended in the atmosphere and gaseous pollutants. Particulate matter (PM), which is usually measured based on particle sizes 10µm (PM_{10}) and 2.5µm ($PM_{2.5}$), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), and sulphur dioxide (SO_2) are considered to be very harmful to human health (Colls, 2002).

The impacts of increased air pollution can vary greatly, both spatially and temporarily, from localised urban population health impacts to regional acidification, and global stratospheric ozone depletion (Fenger, 1999). Local urban pollutant concentrations at any one location can also have spatial and temporal variations, for example, distance from transport networks and traffic density can influence NO_2, $PM_{2.5}$, PM_{10} and CO, concentrations from vehicle outputs. Conversely, O_3 is a secondary pollutant that develops as a result of changes to directly emitted pollutants, such as hydrocarbons and oxides of nitrogen, by ultraviolet light (Ayres, 1998; Colls, 2002). These atmospheric chemical reactions and meteorological factors often result in higher O_3 concentrations being present some distance away (often downwind) from urban zones (Ayres, 1998; Fu et al., 2009).

It is well documented that these pollutants have negative impacts on human respiratory and cardiovascular health (Brunekreef & Holgate, 2002; Schwela, 2000), and contribute an estimated 40,000 deaths annually in the UK (2016 data) (Royal College of Physicians, 2016). Air pollution also has widespread environmental impacts (Colls, 2002), and furthermore, several studies have linked increased air pollution exposure and consequences to urban residents and socially vulnerable populations (Benmarhnia et al., 2014; Jerrett et al., 2004; Makri & Stilianakis, 2008). After the reduction in primary air pollution emissions, an increasingly acknowledged aid for air quality improvement in urban areas is the effectiveness of vegetation to filter air pollution (Hewitt et al., 2020). At present research investigating the potential of brownfield vegetation to mitigate air pollution is lacking. Current literature has focused on brownfield as a source of air pollutants through the phase change of polluted brownfield soil particles to the atmosphere (Jennings, Cox, Hise, & Petersen, 2002; Nijkamp, Rodenburg, & Wagtendonk, 2002). Other studies have examined the theoretical reduction in air pollution from transport that could be gained from shorter commuting distances if urban brownfield is developed in preference to greenfield developments (Mashayekh, Hendrickson, & Matthews, 2012).

2.2.2.2 Climate change impacts

Anthropogenic emissions of GHGs have resulted in changes in the Earth's climate, and projections of climatic changes over the 21st century indicate increased global warming and a heightened prospect of the increasing frequency, extent and duration of extreme weather events, such as heat waves and heavy rainfall (IPCC, 2014; Jenkins et al., 2009). In the urban environment the impacts of these events are exasperated by changes in land cover, where artificial impervious materials replace natural/semi-natural pervious and vegetated land. The materials utilised, and the modifications made, lead to increased albedo, thermal conductivity and radiation (Oke, 2002; Stewart & Oke, 2012; Taha, 1997). These changes can result in determinate alterations in temperature in urban areas when compared to rural vicinities creating an urban heat island (UHI) effect (Oke, 2002; Skelhorn, 2013).

Carbon dioxide is the primary and the most rapidly increasing GHG, principally caused by combustion of fossil fuel and deforestation (IPCC, 2014; Nowak, 1993). To mitigate the impacts of climate change, cities are increasingly focussing on reduction of GHGs, particularly carbon dioxide, as well as preserving carbon stores and enhancing carbon sinks (Gill et al., 2007; Lorenz & Lal, 2015; Mi et al., 2019; Seto et al., 2012). Carbon emission reductions are being achieved through renewable energy and improving efficiency (Mi et al., 2019), and research has increasing emphasised that vegetation, trees and soils can provide a significant carbon sink (Davies, Edmondson, Heinemeyer, Leake, & Gaston, 2011b; Lorenz & Lal, 2015). Many regions are also implementing tree planting regimes, for instance in the UK targets have been set which aim to increase tree planting to 7,000 hectares a year by 2024 in an effort to achieve net zero emissions by 2050 (Defra, Forestry Commission, Natural England, & Rt Hon George Eustice MP, 2021). Planting trees is regarded as a mitigating strategy to offset anthropogenic climate change as carbon stored in tree biomass would otherwise contribute to atmospheric carbon dioxide. Changes in vegetated urban land cover decrease biomass and urban carbon stores, and are associated with increased levels of atmospheric carbon dioxide (Hutyra, Yoon, Hepinstall-Cymerman, & Alberti, 2011; Seto et al., 2012). A number of studies have examined carbon capture by urban biomass, for example, urban parks (Lindén, Riikonen, Setälä, & Yli-Pelkonen, 2020), woodland, agriculture (De la Sota, Ruffato-Ferreira, Ruiz-García, & Alvarez, 2019), though brownfield literature tends to focus on brownfield soil carbon stocks (Jorat et al., 2020; Lord & Sakrabani, 2019; Lorenz & Lal, 2015). Thus, accounting for carbon stores in urban land uses, like brownfield, that are likely to be modified, could be important to assess potential reductions in biomass and carbon stores in cities.

2.2.2.3 Flood risk

Hydrological processes are also altered when impervious construction materials create expansive sealed surfaces, the installation of which can result in reduced infiltration of water to the soil, reduced capture of rainfall, and reduced evapotranspiration (Oke, Mills, Christen, & Voogt, 2017; Taha, 1997). Furthermore, increased rainfall may occur because of altered atmospheric gases, increasing the amount of aerosols and condensation nuclei (particles in the atmosphere on which water vapor condenses) intensifying precipitation (Liu & Niyogi, 2019). Urban areas commonly experience both fluvial (river) and pluvial (surface water) flooding, with sea flooding and inundation also impacting coastal communities (Houston et al., 2011). Urbanisation results in increased velocity and volume of surface water runoff due to the prevalence of impermeable surfaces which increases the likelihood of pluvial flood events (Oke et al., 2017; Taha, 1997).

Urban pluvial flooding is primarily caused by brief intense rainfall events which cannot be displaced by sewers, drainage systems, water courses or infiltrate into pervious ground rapidly enough, which results in overland flow or pooling of water (Bradford et al., 2012; Houston et al., 2011). Fluvial flooding occurs with the increased and overflowing water levels of water bodies extruding into adjacent land due to excessive precipitation (Houston et al., 2011). Incidents of flooding can cause both psychological and physical strain to the populations impacted (Gill, 2006), especially the elderly, the young, and those with existing health conditions or living in areas of social and economic deprivation (Lindley et al., 2011; Pelling, 2012). Flood events can also affect critical infrastructure such as water and electricity supplies, damage buildings (Lindley et al., 2011; Pelling, 2012) and disrupt to emergency services (Pelling, 2012). Urban flood events are expected to increase as urbanisation continues (Defra, 2012).

Sustainable Urban Drainage Systems (SUDS), are installed in current and new urban landscape modifications to reduce the potential impact of impervious surfaces by reducing runoff and slowing down water movement in urban areas (Fletcher et al., 2015; Uzomah, Scholz, & Almuktar, 2014). Their aim is to replicate natural pervious surface substrates and the drainage capacity present before development (Fletcher et al., 2015). Whilst it is acknowledged that brownfield can contribute to the reduction of run-off, this is usually explored via green modification of brownfield (De Valck et al., 2019; Mehdipour & Nia, 2013). Nature-based solutions on brownfield have been suggested such as the construction of wetland, which can provide socio-ecological benefits whilst reducing flood risk (Song et al., 2019). However, lack of large open space in urban areas to install nature-based solutions such as this has been identified as a key barrier (Dhakal & Chevalier, 2017; Uzomah et al., 2014). Uzomah et al. (2014) recommends that if trees and other vegetation were incorporated into brownfields retrofitted with SUDS then smaller sites could benefit urban areas by providing additional natural drainage or interception mechanisms (Section 2.3.2). However, there is a paucity of research examining the current potential or spatial association of brownfield in areas of flood risk or run-off reduction.

2.2.3 Social vulnerability

Densely built-up urban areas can contain highly concentrated populations leading to a greater risk of exposure to environmental hazards such as flooding and air pollution. Furthermore, exposure to increased environmental hazards such as flooding and air pollution (Hall, Duit, & Caballero, 2008; Hall, 2006). Exposure to increased environmental hazards can disproportionately impact the most vulnerable communities in urban settings who are typically less able to prepare, respond and recover to an event (Cutter et al., 2003). Social vulnerability to environmental hazards encompasses the susceptibility or risk of individuals or communities to harm or loss from an environmental event such as a flood, heatwave or decreased air quality (Garbutt, Ellul, & Fujiyama, 2015; Ge et al., 2017; Mitchell, 2017). This is related to their inequitable status within the wider population (Adger, 2006). Vulnerable communities are often in high density, low income areas (Cutter et al., 2003) where there is disproportionate urban development (Hutch et al., 2011), and lower provision of accessible green space (Mitchell & Popham, 2007; Wolch et al., 2014), which increases the risk of environmental hazards (Oke, 2002).

Most research recognises identical or similar dimensions such as age, health and wellbeing, gender, ethnicity, and economic status, population density, which may increase vulnerability to harm encountered due to exposure to hazards (Cutter, Emrich, Webb, & Morath, 2009; Fatemi, Ardalan, Aguirre, Mansouri, & Mohammadfam, 2017). This is because aspects of these dimensions can impact the ability to prepare for, respond to, and recover from exposure to environmental hazards (Cutter et al., 2003; Cutter et al., 2009; Romero Lankao & Qin, 2011). For example, age, health and economic status may affect; the physical or financial ability to modify or insure properties in preparation, lack of access to transport or limited mobility to respond or relocate, and inability to make or afford repairs to aid recovery (Cutter et al., 2003; Lindley et al., 2011). Ethnicity, education, and language proficiency may also hinder these abilities due to lowered ability to comprehend warning information in order to prepare, lack of access to cultural or social aid networks to assist response, or inability to understand or access recovery information (Cutter et al., 2003; Morrow, 1999).

Gender, living arrangements, and housing status can also have impacts. For instance, single parent families, the majority of which are supported by women, may be hindered by financial inequalities, impacting preparedness, and recovery, and slower response times if caring for dependents; also true for household composition where the ratio of adults to dependents (either age or health status) and homes with large families can be financially constrained, with slow response times (Cutter et al., 2003; Morrow, 1999). Further examples of socio-economic and demographic status and their impacts on the ability of people to prepare, respond and recover, and access information are comprehensively described in the literature (Cutter et al., 2003; Fatemi et al., 2017; Kazmierczak, 2012; Tapsell, McCarthy, Faulkner, & Alexander, 2010) .

Many past social vulnerability studies have identified and used data and indicators to represent these demographic and socio-economic factors (Cutter et al., 2009; Fatemi et al., 2017). These indicators provide measurable evidence allowing the simplification, interpretation, understanding or perception of a larger, significant or more complex phenomena (Hammond, 1995), and most often data variables to represent them are sourced from censuses and government databases for social vulnerability research (Willis & Fitton, 2016). Most social vulnerability research uses common indicators which may also include aspects of built environment (Fatemi et al., 2017), and many areas comprising extremely socially vulnerable communities are located in urban centres, and this is prominent in Greater Manchester, where clusters of high social vulnerability have been identified in urban centres (Kaźmierczak & Cavan, 2011).

Cutter et al. (2003) first outlined the concept that social vulnerability was not only attributable to social inequalities, but also a result of spatial or place inequalities, i.e. the interaction of vulnerable communities with the built environment and its environmental conditions. The concept of urban as a multifaceted network or system (Meerow & Newell, 2019), rather than a geographical theme of study, has led to the exploration of the links between social vulnerability, environmental hazards and the built environment that can influence the risk of exposure for the vulnerable. Many studies have found relationships between increased environmental hazards and the socially vulnerable, including the study of climate and natural hazards (Frigerio & De Amicis, 2016; Wilson, Richard, Joseph, & Williams, 2010), or focus on specific hazards such as flooding (Chakraborty, Rus, Henstra, Thistlethwaite, & Scott, 2020; Fernandez, Mourato, Moreira, & Pereira, 2016; Garbutt et al., 2015; Hebb & Mortsch, 2007; Kaźmierczak & Cavan, 2011; Rufat, Tate, Burton, & Maroof, 2015; Sayers, Penning-Rowsell, &

Horritt, 2018; Tapsell, Penning-Rowsell, Tunstall, & Wilson, 2002), air pollution (Bae, Kang, & Lim, 2019; Curtis, Rea, Smith-Willis, Fenyves, & Pan, 2006; Ge et al., 2017; Makri & Stilianakis, 2008), and excessive urban heat (Kazmierczak, 2012; Mitchell, 2017). Research has also found that the built environment, through different urban land uses, can act to lessen or intensify social vulnerability to environmental hazards (Kaźmierczak & Cavan, 2011; Lindley, Handley, Theuray, Peet, & McEvoy, 2006). The relationship between brownfield and social vulnerability is hitherto relatively unstudied. Furthermore, the potential of brownfield land to reduce the risk of exposure to environmental hazards from a socio-ecological perspective is currently unknown.

2.2.4 Environmental injustice

Environmental justice is a concept focussed on the fair distribution of both positive and negative environmental components and their impacts, including access to green space, ecosystem service provision, and exposure to environmental hazards (Jennings et al., 2012; Mohai, Pellow, & Roberts, 2009). Those most impacted by environmental injustice in cities have been identified as the socio-economically deprived and ethnic minorities in cities (both dimensions of social vulnerability) (Mohai et al., 2009; Sister et al., 2010). Much of the research over the last 10-20 years has focussed on measuring the equity of access to green space, and the health impacts linked to lack of access (Jennings et al., 2012; Mitchell & Popham, 2007; Mitchell & Popham, 2008; Schüle et al., 2017b; Sister et al., 2010; Wolch et al., 2014).

Wolch et al. (2014) explain how the history of inequality and oppression, park design, land development, and leisure trends, account for the unequal distribution of green space access in cities. One example is that of parks, which have been shown to be inequitably distributed geographically in cities (Oh & Jeong, 2007), where park supply is low in urban centres and an abundance of green space exists as urban areas transition from suburban to peri-urban to rural gradients (Heynen, Perkins, & Roy, 2006; Ji, Zhang, Liu, Zhong, & Zhang, 2020). Wolch et al. (2014) reports that the installation of additional green space to help combat environmental injustice has become a priority in many urban planning polices. However, Haaland and van Den Bosch (2015) state that urbanisation and development of land in cities is rarely offset by the installation of additional green space, and that available land for green space is lacking. In this context, it is important to highlight that brownfield sites have been found to be disproportionately located in densely built, low income areas, with high levels of social deprivation (Bambra et al., 2015).

2.3 Resilience approaches

The concept of resilience has been defined as the capacity of a system to recover quickly to its original state following natural or anthropogenic pressures or disturbances (Holling, 1973). Socio-ecological resilience is not about attaining an optimal state of this system but about changing and adapting to maintain the equilibrium of the system in the face of pressures and disturbances (Holling, 1973; Levin, 2005). Resilience has been widely studied, including from biological, ecological, and sociological perspectives (Herrman et al., 2011; Holling, 1973; Meerow & Newell, 2019), with the study of urban resilience to climate change and environmental hazards becoming increasingly significant over the last decade (Meerow & Newell, 2019). Meerow et al.'s (2016) definition of urban resilience identifies the complex dynamics of a city that are interconnected and required to adapt to pressures or disturbances to exhibit resilience, and these include social and ecological systems.

Leichenko (2011) classified urban resilience studies into four groups (i) ecological resilience, (ii) the reduction of hazards and risks, (iii) economic resilience, and, (iv) the institutional promotion of resilience. Most research has focussed on social aspects of resilience (Francis & Chadwick, 2013), and Adger (2000, p. 347) defines social resilience as "the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change", which is inextricably linked to social vulnerability. To address these external stresses and disturbances, responses targeting particular aspects of a hazard and its effects are required (Folke, 2002). In terms of planning responses to environmental or natural hazards, these usually encompass the installation or redesign of man-made (or grey) infrastructure to aid future resilience, e.g. flood defences, or reduce energy or material uses, or reduce emissions (Schäffler & Swilling, 2013). Today, some argue that the installation of green (rather than grey) infrastructure, which can provide important ecosystem services, is critical to enhancing urban resilience as cities and populations grow (Schäffler & Swilling, 2013; Staddon et al., 2018), which relates to the definition of socio-ecological resilience above (Holling, 1973; Levin, 2005). The provision of additional urban green infrastructure through innovative design will ensure that environmental justice is more widespread across the city (Wolch et al., 2014).

2.3.1 Urban green infrastructure

The concept of green infrastructure has been referred to as an elevation of the term urban green space (Tzoulas et al., 2007), encompassing all urban ecological systems, as the "interconnected network of green space that conserves natural ecosystem values & functions and provides associated benefits to human populations" (Benedict and McMahon, 2002, p.5).

Previous research into the effectiveness of urban green infrastructure, for urban adaptation and resilience to environmental hazards, has examined benefits provided by; urban parks, woodland, open spaces, waterways, green roofs, riparian systems, street trees and gardens (Benedict & McMahon, 2002; Bolund & Hunhammar, 1999; Gill et al., 2007; Kuittinen, Zernicke, Slabik, & Hafner, 2021; Tzoulas et al., 2007; Woch et al., 2016; Wolch et al., 2014). Figure 2.2 presents examples of green infrastructure in an urban environment. Singular components, such as a tree, are not usually considered as green infrastructure unless connected or associated with other green components or spaces, and it is the network or critical mass concept which is associated with the multiple benefits provided by green infrastructure (Naumann, McKenna, Kaphengst, Pieterse, & Rayment, 2011).

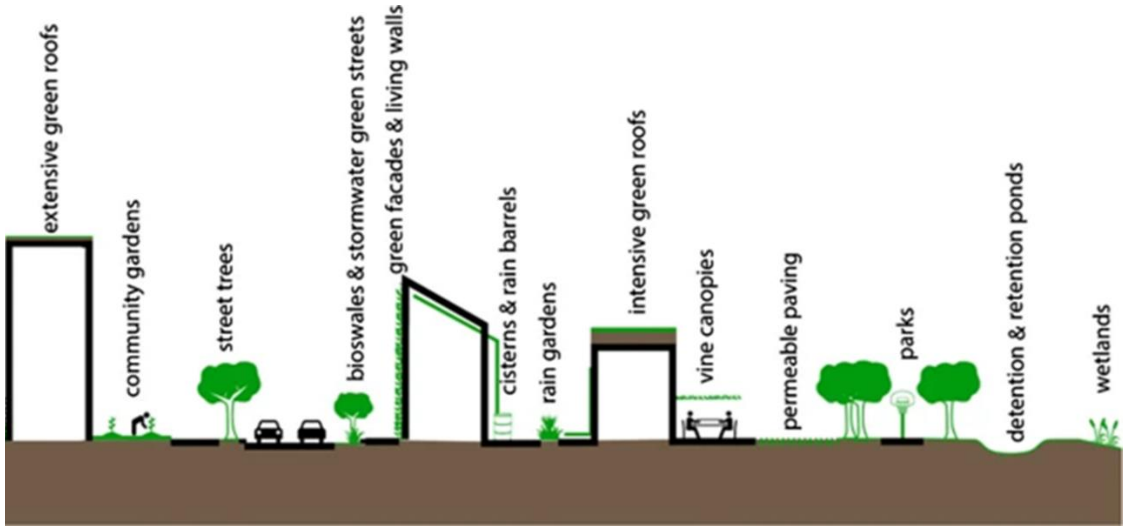


Figure 2.2: Examples of green infrastructure in an urban environment. Source (Elliott et al., 2020).

Many green or vegetated spaces within the city were not originally constructed with environmental protection or urban resilience in mind, focussing on recreation, aesthetics, sources of water, shade or purely as symbols of affluence (Francis & Chadwick, 2013), though links to human health and wellbeing do date back millennia (Ward Thompson, 2011). More recently, these well-maintained green spaces are now recognised as a component of urban green infrastructure and important for urban resilience (Staddon et al., 2018; Wolch et al., 2014), as they provide a wealth of social, economic and environmental benefits (Chiesura, 2004; Koc, Osmond, & Peters, 2017; Konijnendijk, Annerstedt, Nielsen, & Maruthaveeran, 2013; Sadeghian & Vardanyan, 2013) including; ecosystem service provision (Mexia et al., 2018), supporting urban biodiversity (Deák, Hüse, & Tóthmérész, 2016), and health and wellbeing (Ward Thompson, 2011).

The numerous benefits provided by green infrastructure have been categorised into four umbrella functions in a European Commission (2012) in-depth report on the multi-functionality of green infrastructure. These include i) protecting ecosystem state and biodiversity, ii) protecting ecosystem functioning and promoting ecosystem services, iii) promoting the health and well-being of society, and iv) supporting a green economy and sustainable development (European Commission, 2012). As such, the installation of green infrastructure is widely cited and promoted as a solution to lessen negative environmental impacts associated with increased urbanisation (Ahern, 2007; Tzoulas et al., 2007). The recognised benefits of trees and other vegetation for regulating environmental hazards has driven the installation of additional urban green infrastructure, through tree planting, vegetation establishment or the introduction of green walls (Hewitt, Ashworth, & MacKenzie, 2020), green roofs (Berardi et al. 2013), and other innovative greening projects (Mell, 2008). One example is the concept of micro-forests, attributed to Miyawaki (1998), and gaining popularity in Europe (Lewis, 2020), these small forests are densely planted using local native species in urban areas to increase ecosystem service provision.

Ecosystem services provided by green infrastructure and its components aid urban adaptation and resilience to environmental hazards (Bolund & Hunhammar, 1999; Bowler, Buyung-Ali, Knight, & Pullin, 2010; Elmqvist, Gómez-Baggethun, & Langemeyer, 2016; Elmqvist et al., 2015), and it is trees within these areas that provide a significant proportion of the functionality of green infrastructure (Bolund & Hunhammar, 1999; Davies et al., 2011b; Dobbs, Escobedo, & Zipperer, 2011). Trees have been described as the principal and most noticeable components of green infrastructure and ecosystem service provision in urban areas and play a key role in a city's resilience to environmental hazards (Bolund & Hunhammar, 1999; Elmqvist et al., 2016; Livesley et al., 2016).

Research into ecosystem service provision by urban green infrastructure, including trees and tree canopy cover, is increasing, helping to provide evidence of the benefits provided in urban areas (Haase et al., 2014). These include their ability to filter air pollution, regulate ambient air temperatures, store and sequester carbon, reduce flood and stormwater runoff, improve water quality, reduce noise, improve aesthetics in grey spaces, and their value for increased health and wellbeing (Bolund & Hunhammar, 1999; Demuzere et al., 2014; Gill et al., 2007; Nowak, Robert III, Crane, Stevens, & Walton, 2007). This abundance of research into the effectiveness of green infrastructure for urban adaptation and resilience, has mainly focussed on the benefits of conventional green space such as; parks, woodland, green roofs, riparian systems, street trees and gardens (Benedict & McMahon, 2002; Bolund & Hunhammar, 1999; Gill et al., 2007; Tzoulas et al., 2007; Woch et al., 2016). Interestingly, green roof installations are often modelled on brownfield habitat, though often for the purpose of urban biodiversity and the attraction of rare invertebrates (Brenneisen, 2006; Lorimer, 2008). However, the physical status of the network of brownfields at a city scale and their current contribution to green infrastructure is not known.

2.3.2 Urban ecosystem services

The array of benefits provided to humans by natural environments and ecological systems such as green infrastructure are termed ecosystem services (The Millennium Ecosystem Assessment (MEA), 2005). The MEA (2005) classifies ecosystem services into four main categories included provisioning, regulating, cultural and supporting services. Provisioning ecosystem services comprise of any physical products attained from ecosystems, these include food, water, fibres, fuel, and medicines. Cultural ecosystem services offer the non-material benefits humans gain from ecosystems (Potschin & Haines-Young, 2016). These include spiritual experiences, recreation, enjoyment, knowledge, social interaction, and aesthetic values (Potschin & Haines-Young, 2016). Regulating ecosystem services include benefits resulting from the control of ecosystem processes that can impact human functions, including how biotic organisms interact with an environment, such as the regulation and interactions with the movement and cycle of solids, gases, and liquids through the environment (Potschin & Haines-Young, 2016). Supporting ecosystem services (sometimes referred to as habitat services), underpin the other ecosystem services categories, required for their production, including, the production of biomass, the cycling of nutrients, the provision of habitats, and evolutionary and genetic processes for example (MEA, 2005).

The research undertaken for the MEA discovered that most ecosystem services are declining as human use increases (Carpenter et al., 2009). Thus expanding urban areas, where most people reside, require research, analysis and mapping of ecosystem services, and scientific publications in these areas have grown substantially in the last decade (McDonough, Hutchinson, Moore, & Hutchinson, 2017). Francis and Chadwick (2013) emphasise that the three main providers of ecosystem services in urban areas are vegetation, water, and soil, or green, blue, and brown infrastructure. Thus, the identification, quantification, and mapping of these three land cover classes provides good indicators of ecosystem services within urban areas, or within sub-domains or land use categories contained within them (Koschke, Fürst, Frank, & Makeschin, 2012).

Another aspect of ecosystem services is that they have distinct spatial impacts, with some ecosystem services providing localised (close to source) impacts or benefits, whilst others contribute to global (distant from source) ecosystem services benefits (Bolund & Hunhammar, 1999). For instance, carbon sequestration and storage by vegetation in urban areas provides a global benefit by reducing atmospheric concentrations of the well-mixed greenhouse gas carbon dioxide; air pollution regulation by vegetation can provide benefits at both local and wider scales (Bolund & Hunhammar, 1999). However, noise regulation, for example, would provide benefits only at the local source of the hazard (Bolund & Hunhammar, 1999). This trade-off is handled by adjusting the spatial scale at which ecosystem services are modelled or mapped, for example air pollution and flood risk can be localised or regionally located, and thus would require indicators at an appropriate unit of scale (Kruse, 2017). Regulating ecosystem services have most commonly been mapped at national scale (Crossman et al., 2013; Egoh, Drakou, Dunbar, Maes, & Willemen, 2012).

2.3.3 Ecosystem services of urban green infrastructure

Urban trees and other vegetation act as a sinks of carbon dioxide by fixing carbon as biomass through the process of photosynthesis (Nowak & Crane, 2002; Nowak, Greenfield, Hoehn, & Lapoint, 2013). The amount of carbon stored is proportional to the amount of biomass, thus the increase or growth of vegetation in urban areas results in increased stores of carbon. The reverse is also true, in that vegetation, dies, is cut, mown, unrooted and decays releasing carbon back into the environment (Nowak & Crane, 2002). Whilst both natural and anthropogenic carbon emissions are significant when compared to the amount stored in biomass, research has estimated above ground urban carbon pools to be considerable (Davies et al., 2011b; Nowak & Crane, 2002; Pataki et al., 2006). Indeed, urban tree canopy cover may have a higher capacity for carbon storage than non-urban forests due to the increased proportion of mature trees and increased growth rates due to decreased competition (Nowak & Crane, 2002). Even low stature urban vegetation such as amenity grassland and lawns can store significant amounts of carbon due to their large spatial coverage, high productivity and increased growth periods (Francis & Chadwick, 2013), though this is lower per unit area than trees (Fowler et al., 2004; Jeanjean, Monks, & Leigh, 2016) (Table 2.1). Additionally, vegetation can have indirect impacts on the reduction of GHG emissions via reduction in energy use due to local cooling (Pataki et al., 2011). Thus, as the UK sets targets to achieve net zero emissions by 2050, and green infrastructure installation within the UK is increased, knowledge of existing green, blue, and brown infrastructure on all urban land use types is essential. However, this is currently limited, with most research focusing on existing formal green spaces, where a broader picture would be gained by mapping the character and complexity of informal urban green spaces (Rupprecht & Byrne, 2014) to provide a broader picture of urban ecosystem services and potential contributors to urban resilience.

Table 2.1: Carbon density for various stature vegetation and an average garden. Table adapted from (Davies et al., 2011b).

Vegetation type	Carbon density (kg/m^2)
Herbaceous	0.14
Shrub	10.22
Tall shrub	14.19
Tree	28.46
An average garden	0.79

Urban trees (and other vegetation) improve air quality by removing atmospheric pollutants (Escobedo & Nowak, 2009). Vegetation can remove gaseous pollutants by absorption by either stomatal uptake or other plant surfaces, and by intercepting airborne air pollutants by dry deposition of both gases and particulates which are retained on plant surfaces, some of which can also be absorbed (Nowak, Crane, & Stevens, 2006). Different plant species have been shown to be more or less efficient at air pollution removal due to the biophysical structure of their leaves, stems, bark (i.e. deciduous or evergreen) and leaf surface types (waxy or rough) (Beckett, Freer Smith, & Taylor, 2000; Dzierżanowski, Popek, Gawrońska, Sæbø, & Gawroński, 2011; Sæbø et al., 2012) (Table 2.2). Temporal variations of air pollutant removal occur due to circadian and annual variations in biophysical functions (Jim & Chen, 2008). For example, stomatal openings close during the evening, and leaves are shed during winter months for many tree species impacting rates of pollutant removal (Jim & Chen, 2008).

Table 2.2: Air pollution removal by different types of vegetation. Adapted from (García de Jalón et al., 2019).

Vegetation type	**Total air pollution removal**	**NO_2**	**O_3**	**SO_2**	**PM_{10}**	**CO**
		kg/ha				
Deciduous trees	41.11	3.49	18.67	0.91	17.72	0.32
Coniferous trees	56.05	6.47	23.44	1.82	23.86	0.46
Mixed forest	44.58	4.2	20.38	1.27	18.38	0.35
Shrub	31.92	3.58	13.32	1.04	13.71	0.27
Natural grassland	7.22	0.79	3.16	0.19	3.02	0.06

Street vegetation may act as a barrier close to pollutant sources (Abhijith et al., 2017), though height, size, position, and leaf structure of green infrastructure needs to be optimised for high pollutant removal potential (Abhijith et al., 2017; Salmond et al., 2013). Urban locations containing a complex combination of vegetation types e.g. trees, shrubs and grasses, may provide higher capacity to remove urban air pollutants by providing a more complete green barrier from the ground up, capable of capturing more pollutants of various particle sizes (Janhäll, 2015a; Vieira et al., 2018). Most air pollution removal estimates for urban vegetation have been based on mean variables at a city scale, with fewer at plot scale (Escobedo & Nowak, 2009). Understanding the composition and structure of vegetation in the field can provide information about the air pollution filtering capabilities of urban green infrastructure for management and planning decisions, prioritising interventions and informing local policy, and to improve the quality of urban environments and human health (Nowak et al., 2008a).

In terms of flood attenuation, vegetation and pervious or permeable surfaces offer natural drainage or interception mechanisms which allow the infiltration of water into the soil substrate, or the capture of water on leaves, stems or trunks of vegetation (Francis & Chadwick, 2013). The infiltration of water into soil depends on the type and current saturation of the substrate (Oke, 2002). Infiltrated water can drain to the groundwater, be absorbed in the soil matrix or be taken up by root systems, whilst water intercepted by vegetation is slowed down, and remaining surface water is mostly evaporated (Francis & Chadwick, 2013).

2.4 Brownfield characteristics, benefits, opportunities

It has been established that brownfields can contain vegetation, and other pervious surfaces (Robinson & Lundholm, 2012; Schadek, Strauss, Biedermann, & Kleyer, 2009), which potentially provide several ecosystem services in urban areas (Francis & Chadwick, 2013), but there is very limited research undertaken on this subject. To date the investigation, quantification, and contribution of urban brownfield types to urban resilience, green infrastructure and associated ecosystem service provision are lacking. Furthermore, whilst vegetated brownfields could logically be included within the concept of green infrastructure, as postulated by Mathey et al. (2015), few studies have considered regulating ecosystem services of brownfield particularly at a city scale. This section will provide an overview of brownfield characteristics, benefits, and examples of opportunities that they present.

2.4.1 Brownfield characteristics

In contemplating urban resilience, and the installation of green infrastructure, one problem that is often discussed is the provision and location of space for such schemes (Haaland & van Den Bosch, 2015; Meerow & Newell, 2019). However, one specific land use with the extent, location, and potential for green infrastructure installation is brownfield. Brownfields are prevalent in urban, sub-urban, and peri-urban areas (Bambra et al., 2014; Grimski & Ferber, 2001; Nassauer & Raskin, 2014), though primarily located in built up urban zones, within or adjacent to highly impervious industrial, commercial and residential areas (Hollander et al., 2010). Brownfields are also typically located in close proximity to roads (Gorman, 2003), highly impervious urban areas, or located next to rivers and other waterbodies (especially older industrial units) (Gorman, 2003). It has been shown how brownfields are disproportionately located across urban areas (Oliver et al., 2005), where exposure to environmental hazards is greater (Oke, 2002), vulnerable people may reside (Cutter et al., 2003), and there is a lack of access to green space (Haaland & van Den Bosch, 2015; Mitchell & Popham, 2007).

These spatial aspects of brownfield e.g. close sources of air pollution (roads) may offer the potential of improving local air quality if vegetated. This also brings into focus the potential of brownfield land for the interception of surface and river flood water which has not been widely applied (Song et al., 2019) or studied. These areas could represent, or potentially be transformed into, natural pervious and vegetated areas, or they could be repurposed as artificial flood ways or plains (De Valck et al., 2019; Mehdipour & Nia, 2013). As urbanisation increases through the development of urban brownfield, and the importance of urban resilience intensifies, there is a paucity of research exploring how brownfield ecosystem services are distributed across urban areas, and how these compare to ecosystem benefits by existing green infrastructure.

Koc et al. (2017) found that green infrastructure literature generally grouped resources into four categories: i) tree canopy, ii) green open spaces, iii) green roofs, and iv) vertical green systems. It is within the green open space category that brownfield is most often identified as a component of green infrastructure (Koc et al., 2017), typically as a single land use type, and not identifying specific features within them which may be providing benefits to urban areas. To include brownfield in open green space typologies implies that all brownfield is vegetated space and without significant tree cover. This identifies a gap in the literature, where the consideration of the complete stock of brownfield sites in cities, both vegetated and impervious, would benefit the study of urban green infrastructure components, their location, distribution, and their functionality.

Brownfields are commonly perceived as long abandoned industrial landscapes, with rusting machinery, decaying infrastructure, derelict structures, unkempt weeds (Gorman, 2003; Hollander et al., 2010), crime (Kim et al., 2018), and litter (Kamvasinou, 2011) (Fig. 2.3). Moreover, brownfields are often perceived to contain hazardous substances, pollutants or contaminants (Rizzo et al., 2015). This may include potentially toxic heavy metals and metalloids such as lead (Pb) and arsenic (As), inorganic chemicals like asbestos, organic compounds such as petroleum hydrocarbons and even elevated radiation levels (Environment Agency, 2005; Health Protection Agency, 2010). The Environment Agency (2002) note that most contamination levels on UK brownfield are not excessively high and often do not meet the statutory definition of contaminated land. Detailed knowledge of past land uses, the discarding of waste products, chemical spillages, spread of contaminated particulate matter and land disturbances are usually unknown (French et al., 2006), and thus perceptions of brownfield contamination are inaccurate (Page and Berger (2006).

Figure 2.3: An example of a brownfield site with decaying infrastructure. Image (Authors image, 2018).

Furthermore, brownfields also vary in size from small individual residential plots to extensive sites left over from terminated mineral extraction, landfill and manufacturing activities, for example (Bambra et al., 2014; Grimski & Ferber, 2001). Brownfields often contain residual characteristics of their former land uses. These include diverse surface cover conditions such as, built structures, remnants of buildings such as foundations, rubble and other debris, impervious surfaces, and compacted or disturbed soils each of which have their own physical and chemical properties (Gilbert, 1995).

2.4.2 Brownfield benefits

Many brownfield sites are left undisturbed after abandonment, sometimes for years, allowing spontaneous vegetation succession to take place (Bonthoux et al., 2014; Schadek et al., 2009), providing niche habitats (Angold et al., 2006; Bonthoux et al., 2014; Schadek et al., 2009), and allowing many species of flora and fauna to flourish (Eyre, Luff, & Woodward, 2003; Maurer, Peschel, & Schmitz, 2000). An example of a single brownfield site containing several niche habitats and flora are presented in Figure 2.4. These species benefit from associations with the unique anthropogenic environments, and the artificial habitats that humans create in urban areas (Gilbert, 1995). Abundant wildlife often includes many rare and endangered species (Maurer et al., 2000), alongside more widespread and common species (Gilbert, 1995).

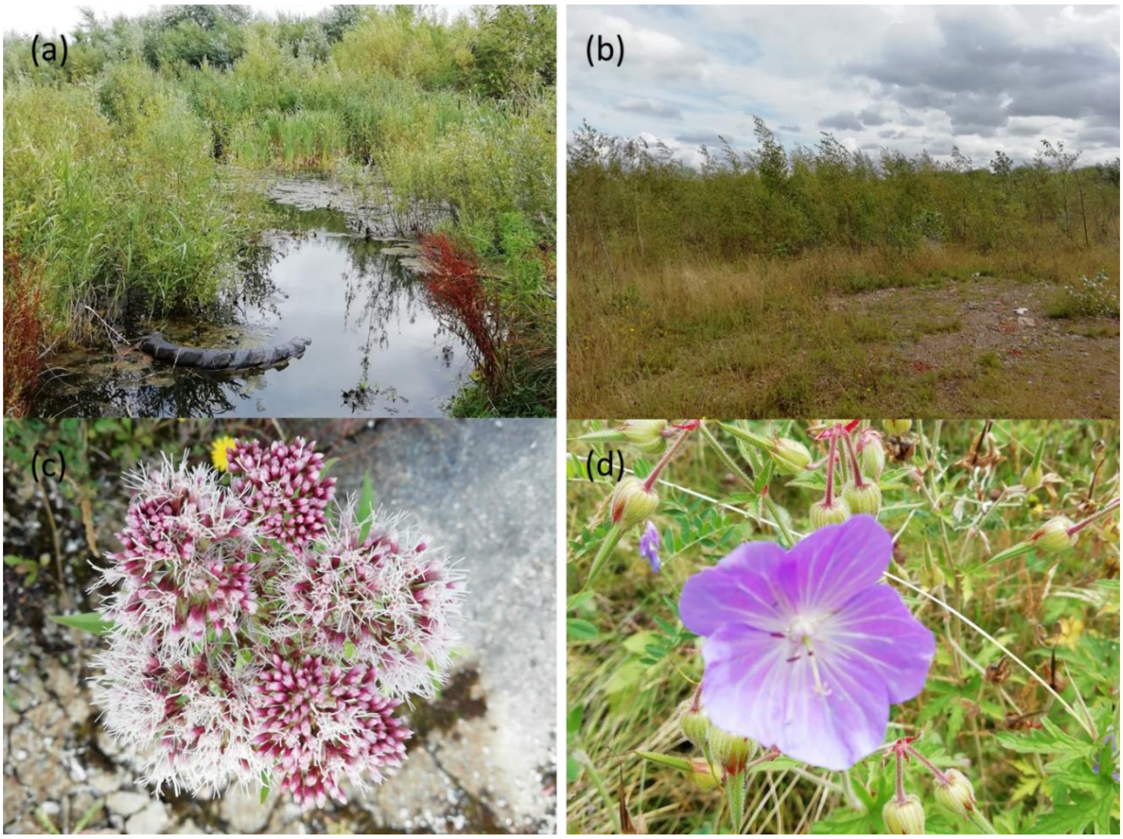


Figure 2.4: Examples of several niche habitats and flora on the same brownfield site in Greater Manchester. (a) wetland, (b) young birch and willow woodland, grassland, bare substrate, (c) Hemp agrimony (Eupatorium cannabinum) normally found in damp grassland, marshes, fens and wet woodlands, riverbanks, calcareous soils, (d) Meadow crane's-bill (Geranium pratense) normally found in lowland hay meadows, grassland and calcareous soils (Streeter, 2009). Images: (Authors images, 2019).

While current planning policy does not consider the actual or potential value of brownfield in terms of ecosystem service provision, there is some consideration of the role of brownfield in supporting biodiversity. Open Mosaic Habitats (OMH) on Previously Developed Land are an early successional habitat, found on brownfield, and have been included in the UK Biodiversity Action Plan (UKBAP) as a Priority habitat since 2006 (Biodiversity Reporting and Information Group (BRIG), 2011). The definition of OMH states that several criteria be met. They must be at least 0.25ha in area, have a known history of ground disturbance, contain spatial variation of one or more early successional and stress tolerant communities, and unvegetated loose substrate or pools (BRIG, 2011). However, currently there is high uncertainty of the true extent of this habitat due to its transitional nature and difficulties in identification, with on-site environmental audits such as Phase One Habitat Survey being required to confirm its presence (Joint Nature Conservation Committee, 2010; Lush, Shepherd, Harvey, Lush, & Griffiths, 2013). OMH is a transitional and dynamic habitat, and eventually natural succession can lead to woodland establishment, by which time it ceases being a priority habitat (Kirklees Council, 2019). However, it could still hold a high intrinsic biodiversity value as a woodland habitat whilst simultaneously delivering greater overall ecosystem service provision. The life span of OMH is approximately 15-20 years if left undisturbed (Macadam, Bairner, & Cathrine, 2013). Macadam et al. (2013) suggest that a brownfield-first redevelopment approach could preserve OMH by redeveloping sites without OMH or those at the end of its natural lifespan first. However, low accuracy in mapping techniques, and the extent of brownfield requiring onsite surveys to confirm OMH presence, would likely make this scenario challenging. Currently, OMH is usually identified in pre-development surveys, when it is recommended that habitat disturbance be avoided, mitigated or compensated for based on its identified value (Ministry of Housing Communities & Local Government, 2016).

Brownfields can contain vegetation, water and bare earth which provide ecosystem services in urban areas (Bonthoux et al., 2014; Francis & Chadwick, 2013; Gilbert, 1995; Schadek et al., 2009; Wheater, 1999). Several studies have examined the biodiversity often promoted by brownfield habitats (Angold et al., 2006; Bonthoux et al., 2014), and their ability to provide niche habitats for rare and specialised species (Angold et al., 2006; Eyre et al., 2003). Several others have examined cultural or recreational ecosystem services, and perceptions of brownfields (including Pueffell et al., 2018, Mathey et al., 2018, and Threlfall and Kendal, 2018). These studies generally find that brownfields are valued by many people within their local areas, though this depends on the physical or successional status of the site (Mathey, Arndt, Banse, & Rink, 2018; Mathey et al., 2015; Rall & Haase, 2011). However, few studies have attempted to quantify ecosystem service provision (Koch et al., 2018), and there is a paucity of research about brownfield flood attenuation, air pollution removal and carbon storage and sequestration, especially in the UK.

Investigating regulating ecosystem services on brownfield, Mathey et al. (2015) utilised climate modelling (Envi-met) to assess microclimate regulation of vegetated brownfield, and found that brownfields were comparable to other urban green spaces depending on successional stage. Using a similar approach, Koch et al. (2018) found that with smart urban planning approaches, and incorporating green space into brownfield redevelopment plans, brownfield redevelopment does not necessarily result in negative impacts on local microclimate. Other studies have investigated brownfield regulating services provided by soils finding significant carbon storage and sequestration potential (Herrmann, Shuster, & Garmestani, 2017; Jorat et al., 2020).

Kim et al. (2018) assessed several types of vacant lots, including both previously developed and undeveloped land, and found derelict sites in Roanoke, US, with 32.5% tree cover sequestered 534.8 kgC/ha/yr, while post-industrial sites with 13.5% tree cover sequestered 99.4 kgC/ha/yr, though no direct comparisons were made with other green infrastructure types. McPhearson, Kremer, and Hamstead (2013) and Kremer, Hamstead, and McPhearson (2013) assess multiple ecosystem services at vacant lots across the US, with vacant lots providing significant regulating ecosystem services, food production and in regular use for public, private and commercial purposes. However, it must be noted that the term vacant lots and the data source used in these US studies defines vacant lots as land having no improvement or constructive use. This can be misleading; for example, vacant lots (often used in US studies) may have multiple descriptions within classifications (Kremer et al., 2013), and they can be both previously developed and undeveloped, or be identified as a separate entity to previously developed land (Pagano & Bowman, 2000). Thus, vacant lots are not representative of the UK brownfield definition. Whilst these studies emphasise some potential of vacant lots in providing ecosystem services, literature investigating multiple regulating ecosystem services by brownfield vegetation is deficient in comparison, especially in the UK at the city scale. There are several limiting factors associated with brownfield investigation at a site scale, including physical or administrative barriers (Kamvasinou, 2011), time, labour and resource intensive work, which increase substantially with increasing study area (Rhodes, Henrys, Siriwardena, Whittingham, & Norton, 2015), and difficulties in comparing with other research.

2.4.3 Brownfield opportunities

Despite the potential environmental benefits of brownfield outlined above, the effective redevelopment of brownfield is usually assessed in terms of economic benefits (Frantal, Josef, KLUSÁČEK, & Martinat, 2015), remediation of contamination, or neighbourhood revitalisation (Ganser & Williams, 2007; Longo & Campbell, 2017). Pizzol et al. (2016) argue that a balance between these economic, social, and environmental dimensions is required to be perceived as a sustainable project, that prevents urban sprawl and expansion into green-field or agricultural land, to be a successful (Table 2.3). Although it must be noted that the apparent successful re-use of brownfield can depend on the ratio of importance placed on these dimensions, and other factors, which differ depending on location, type of redevelopment project, and stakeholder values (Doick, Sellers, Castan-Broto, & Silverthorne, 2009). It can be seen in Table

2.1 that the environmental and social benefits of redeveloping brownfield suggest risks from contamination, which as discussed, is not always the case.

Table 2.3: Traditional perceived benefits of successful brownfields redevelopment adapted from Bardos et al. (2016), summarised from Paull (2008)

Environmental
Reduction of greenfield development and urban sprawl
Lower contributions to poor air quality, energy consumption, and carbon footprint due to reduced transport
Water quality benefits (from contamination and site clean-up)
Environmental benefits by reducing negative ecosystem impacts (contamination)
Economic
Increased site value
Increased local property values
Employment and investment opportunities
Avoidance of infrastructure construction
Social
Reduced risk to public health (contamination remediation)
Reduced distance travelled by transport
Amenity benefits such as improved appearance and aesthetics
Health benefits

Whilst temporary land uses have existed parallel to the growth of cities historically, including uses such as circuses, storage, car parks (Stevens, 2018), and agriculture (Slater, 2001), not until recently have brownfield interim uses been utilised especially for the benefit of urban communities (Stevens, 2018). One example is a pre-millennial interim land use policy which was introduced in Leipzig, Germany, to combat urban decay. An agreement between government and private landowners allowed the public to utilise private brownfield land whilst owners retained the right to redevelop the land when appropriate, and land tax exemptions were offered (Song et al., 2019). This resulted in the creation of new urban open green space, and associated benefits (Song et al., 2019).

Use of brownfield by the public, as in the Leipzig example, can also offer incentives to landowners and developers. The simple use of land as a cut-through or shortcut, sometimes termed desire lines can guide redevelopment designs and infrastructure placement (Nichols, 2014). Furthermore, use of some brownfield for public events would generally be accompanied by a tidy up and litter removal by the organisers (Kim, 2016; Németh & Langhorst, 2014), and dissuade crime such as vandalism and fly tipping (De Biasi, 2017). Several examples of brownfield alternative or interim re-use exist in the literature (Table 2.4). These examples of brownfield reuse can provide environmental, social, and economic benefits, including greenways, productive vineyards, community event spaces, and urban agriculture (Figure 2.5). Given the potential and continued demand for open space in our urban areas to combat environmental injustice and contribute to urban resilience, the presence of unused brownfield land necessitates a new approach to brownfield monitoring, management and strategic development approaches (Rall & Haase, 2011). This however requires several challenges to be overcome, with regards to discrepancies in brownfield designation, identification, and classification.

Table 2.4: Examples of brownfield reuse.

Brownfield re-use examples	**Source**
Recreational tracks	Carroll & Kanarek, 2018, Kim, 2016
Cycle paths	Sustrans, 2019, Schilling & Mallach, 2012
Urban agriculture	Kamvasinou, 2017, Deelstra & Girardet, 2000
Woody biomass production	Lord et al., 2008, French et al., 2006
Park	Kremer et al., 2013, Kim, 2016
Informal green space	Carroll & Kanarek, 2018, Kim, 2016
Nature preserves	Kamvasinou, 2011, Kim, 2016
Improve local aesthetics	Rall & Haase, 2011
Community events	Kamvasinou, 2017, Kim, 2016

Figure 2.5: Alternative and interim uses for several types of previously developed brownfield sites with diverse land cover. (a) a greenway developed on an abandoned railway (Manchester, UK), (b) a vineyard planted on the site of demolished tenements (Lisbon, Portugal), (c) a community events space (LX Factory) converted from an abandoned industrial estate (Lisbon, Portugal), (d) a community raised bed growing area on a totally impervious site, (Birmingham, UK). Source: Authors images, 2017-20.

2.5 Brownfield investigation challenges

Several challenges currently exist which limit the investigation of brownfield land. The main challenges include discrepancies in brownfield designation, identification, and classification. Many differences exist as to what constitutes a brownfield in post-industrial countries around the world (Alker, Joy, Roberts, & Smith, 2000a; Grimski & Ferber, 2001; Heasman, Westcott, Connell, Visser-Westerweele, & MacKay, 2011; Oliver et al., 2005; Ramsden, 2010), and the terminology used when describing brownfield sites in current research is diverse. Without a universally accepted definition of brownfield, it is challenging to compare international studies, or provide transferability of methods and approaches. There are also discrepancies in the reporting and identification of brownfield in registers, making it difficult to select study sites or provide a comprehensive analysis of brownfield. Furthermore, there is a paucity of research classifying brownfield sites, which are often mis-represented as a single land use within a wider typology of urban land uses. This section will provide an overview of these challenges.

2.5.1 Brownfield definitions and terminology

Discrepancies in brownfield terms and definitions (Tables 2.5 & 2.6) present challenges for research (and potentially practice), if there is no universal definition of brownfield it is difficult to identify brownfield and select sites for analysis (on the ground). It is also challenging to compare studies based on brownfield when definitions vary so widely, which may lead to confusion for research, practice, and public perceptions. The general understanding is that brownfield is unused space in an urban area that is not a publicly used or natural greenspace (Adams, De, & Tiesdell, 2009; Hollander et al., 2010). However, beyond this there are overlapping and varying definitions globally (Loures & Vaz, 2018; Oliver et al., 2005), with different terminology and different perceptions and uses for the same terms (Alker, Joy, Roberts, & Smith, 2000; Loures & Vaz, 2018), examples of which are described below.

Example 1 contaminated land: Some definitions of brownfield are limited to the contaminated status of a site, such as North America (Adams et al., 2009; De Sousa, 2003; USEPA, 2017), and sites which have no presence of contamination at all are not classified as brownfield (Longo & Campbell, 2017). Other definitions may include contaminated sites but not exclusively, including the UK, where contamination does not factor into the designation of a site as brownfield (though this may well be the case).

Example 2 previously developed land: Some definitions and terms of brownfield require a site to have been previously developed and explicitly refer to this, whereas others do not. Vacant land and vacant lots are examples which can include both previously developed land and/or previously undeveloped land which are not available for development.

As a result of these differing terms and definitions, research focussing on or incorporating brownfield has included land which is not previously developed into their typologies such as, railway sidings, road verges, riverbanks, and green-fields (vacant areas not considered for development, but with no formal use), as well as other land types. Furthermore, this could have potentially influenced the fate of many brownfield sites over the past decades. For example, perceptions of contamination or high costs of remediation may well have influenced many planners and local authorities' decisions with regards to their redevelopment (McCarthy, 2002; Sinnett, Carmichael, Williams, & Miner, 2014). Many sites may have previously been overlooked for redevelopment in favour of larger peri-urban and sub-urban construction projects, where cost per household is relatively cheaper when compared to perceived remediation costs of redeveloping inner-city land (McCarthy, 2002; Sinnett et al., 2014). This thesis adopted the UK definition of brownfield which encompasses previously developed land, contaminated or not, which has potential for redevelopment, which is outlined below.

"land which is or was occupied by a permanent structure, including the curtilage of the developed land (although it should not be assumed that the whole of the curtilage should be developed) and any associated fixed surface infrastructure." (Ministry of housing Communities and Local Government, 2012, para 74).

Table 2.5: Brownfield terminology.

Terminology	Source
Contaminated land	Loures & Vaz, 2018
Wasteland	Bonthoux et al., 2014
Vacant land	Pagano & Bowman, 2004
Derelict land	Hollander et al., 2010
Urban wildscape	Jorgensen & Keenan, 2012
Previously developed	Loures & Vaz, 2018
Abandoned land	Loures & Vaz, 2018
Derelict land	Loures & Vaz, 2018
Demolished	Loures & Vaz, 2018
Drosscape	Berger, 2007
Urban commons	Gilbert, 1995
Vacant lots	Anderson & Minor, 2017
Urban brownfield	Mathey, 2015

Table 2.6: Varying definitions of brownfield.

Country	Definitions	Source
Austria	No official definition. Understanding like CABERNET definition recognising potential for reuse and with less focus on contamination.	Umweltbundesamt Wien (2004) (from Oliver et al., 2005)
Belgium	Sites previously dedicated to economic activities and where the current condition is contrary to 'efficient land use' OR Abandoned or under used industrial sites with an active potential for redevelopment or expansion but where redevelopment or expansion is complicated by a real or perceived environmental contamination	Direction Generale des Resources Naturelles et de l'Environment (DGRNE) AND Openbare Afvalstoffenmaatschapp ij voor het Vlaamse Gewest (OVAM) (from Oliver et al., 2005)
Bulgaria	Contaminated sites – areas where previous activities have ceased but are still impacting on neighbouring areas.	University of Mining and Geology, Sofia (from Oliver et al., 2005)
Czech Republic	Sites that have been affected by the former uses of the site and surrounding land; are derelict and underused; may have real or perceived contamination problems; are mainly in developed urban areas; and require intervention to bring them back to beneficial use.	Czech Brownfield Regeneration Strategy, Progress Report (Czechinvest) (from Oliver et al., 2005)
Denmark	Land affected by contamination.	Danish Environmental Protection Agency (from Oliver et al., 2005)
France	Space previously developed that are temporarily abandoned following the cessation of activity and need to be reclaimed for future use. Can be partially occupied, derelict, or contaminated.	Ministere de l'Environnement (from Oliver et al., 2005)
Germany	Inner city buildings not under use. Inner city areas for redevelopment and refurbishment.	Umweltbundesamt Berlin (from Oliver et al., 2005)
Ireland	Derelict land: Land which detracts, or is likely to detract, to a material degree from the amenity, character, or appearance of land in the neighbourhood of the land in question because of ruinous structures, neglected condition or presence of waste.	Environmental Protection Agency (from Oliver et al., 2005)
Italy	Contaminated site: site that shows levels of contamination or chemical, physical, or biological alteration of soils, sub soils and of superficial or underground water in a way to determine danger for public health or for the natural or built environment. The site must be considered contaminated if the presence of only one of the values of contaminant in soils, sub soils, superficial or underground water is higher than the permitted values of the law.	Italian National Law 426/98 and Italian National Law 471/99 (from Oliver et al., 2005)
Poland	Degraded areas due to diffuse soil contamination - high density of landfill sites.	Ministry of Environment (from Oliver et al., 2005)
Slovenia	Degraded / abandoned building land usually inside urban areas.	University of Ljublijana (from Oliver et al., 2005)
U.S.	A brownfield is a property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant.	USEPA, 2018
U.K.	Land which is or was occupied by a permanent structure, including the curtilage of the developed land (although it should not be assumed that the whole of the curtilage should be developed) and any associated fixed surface infrastructure. This excludes: land that is or has been occupied by agricultural or forestry buildings; land that has been developed for minerals extraction or waste disposal by landfill purposes where provision for restoration has been made through development control procedures; land in built-up areas such as private residential gardens, parks, recreation grounds and allotments; and land that was previously-developed but where the remains of the permanent structure or fixed surface structure have blended into the landscape in the process of time.	(Department for Communities and Local Government, 2012)

2.5.2 Identifying brownfield

There are discrepancies in the reporting of brownfield, and factors such as size and contamination levels may exclude some sites from reporting guidelines. This is a challenge for research as incomplete records of brownfields may lead to an incomplete representation of the stock of brownfield within a city. For example, the Town and Country Planning (Brownfield Land Register) Regulations (2017: 3), England, state that brownfield land must have an area of at least 0.25 hectares or should be capable of supporting at least five dwellings, excluding smaller sites from recent registers. Technologies such as Geographical Information Systems (GIS) have prompted some authorities to produce brownfield registers (i.e. Czech Republic, England) (Coffin, 2003), though these are still likely to be incomplete (Coffin, 2003). Unreported or unnoticed brownfields make it a difficult task to identify all brownfield sites within large cities, and this is supported by the recent call from government and local authorities in the UK to 'parish councils, neighbourhood forums, landowners, developers, businesses and relevant local interest groups' (Ministry of Housing Communities and Local Government, 2019, para. 12), to identify potential brownfield sites and broad locations for development.

One such example of an unreported, or unnoticed, brownfield site is presented in Figure 2.6, which displays a site not included in any brownfield registers, despite being derelict and unused since 2009. Given its previous use as a place of worship it is likely this site is under private ownership (the church) and has not been reported to local authorities by the landowner, or other party as described above. Furthermore, sites included in registers, reported by local authorities, have historically been inconsistent (The Homes and Communities Agency, 2014). Where a brownfield register is not available several methods have been used to identify brownfield, including historical, topographic, contamination, and land use datasets, and it is common practice to utilise multiple available datasets to identify sites (Coffin, 2003; Ferrara, 2008; Hayek, Novak, Arku, & Gilliland, 2010; Kolejka & Klimánek, 2015; Moser, Krylov, De Martino, & Serpico, 2015). A comprehensive and spatially-referenced database of brownfield sites is invaluable as a platform for further investigation of these sites (Hayek et al., 2010).

Figure 2.6: An example of an unidentified/unreported brownfield site. (a) original structure, Image: (Kapp, 5 Sept, 2007), (b) demolition, Image: (Dixon, 3 Feb, 2010), (c) Natural succession (Authors image, 17 Jan, 2018), and (d) close up image (Author's image, 22 Jun, 2018).

2.5.3 Brownfield classification

In many urban studies, brownfields are often identified as a single entity within a wider typology of urban land uses (Table 2.7). This is most likely because the varying terms and definitions portray brownfield as a single type, based on land use designation. Many terms and definitions generate negative perceptions of brownfield as unsafe or unproductive spaces of little environmental value, and negatively impacting local communities and the environment (Kim et al., 2018). This narrow focus, imagining all brownfield to be of little environmental value, in the drive to supply residential and commercial properties, may lead to authorities undertaking uneven development of brownfield based on profit, and in areas where such development is not environmentally, socially or economically sustainable (Tang & Nathanail, 2012). However, as discussed previously (**Section 2.4**) brownfields can be temporally dynamic spaces, where many sites, if undisturbed after abandonment, undergo spontaneous natural succession (Bonthoux et al., 2014). The diverse successional stages found at brownfield sites amount to heterogeneous habitats (Kattwinkel, Biedermann, & Kleyer, 2011). Thus, treating brownfield as a single land use type is a gross oversimplification, especially when comparing with other land use types such as parks, agricultural land, and other green spaces.

A small number of studies have created typologies or classifications of brownfield (Table 2.7). Brownfield classifications have primarily been created for specific purposes, such as identifying redevelopment potential or priority, contamination (Alker et al., 2000b), potential hazards and risks, financial or economic benefits and past and present use (Dasgupta & Tam, 2009). Others have focussed on the identification and monitoring of brownfield and their surroundings to map urban redevelopment and inform decisions for future use (Moser et al., 2015). Recently, some research has incorporated socio-ecological aspects into typologies as the realisation that brownfield can present social, ecological and environmental benefits within urban areas is increasingly acknowledged (Kremer et al., 2013; Mathey et al., 2015) (Table 2.7). However, these typologies are not particularly transferable beyond the immediate study area due to the differing definitions of what constitutes a brownfield in different countries, or the grouping of brownfields into primary groups, such as ‘industrial’ or ‘vegetated’, which does not capture the diversity of brownfields (Alker et al., 2000). As discussed brownfield has been shown to contain a diverse combination of land cover types, featuring pervious surfaces, vegetated areas at various stages of succession, and water bodies, alongside the built structures and impervious surfaces typically imagined as relics of past development (Gilbert, 1995). It is this diversity of brownfield types that has not been comprehensively investigated.

Table 2.7: Examples of brownfield typologies and land uses including brownfield as a category.

Source	Terminology used	Aim of study	Location of Study	Typology based on	Typology
Kolejka & Klimánek, 2015	Post-Industrial Landscape	To identify and classify post-industrial landscape areas	Czech Republic	Land use	(a) Mining, (b) Mining-chemistry, (c) Mining construction, (d) Mining-ceramic, (e) Mining-machinery, (f) Mining-energetic-construction, (g) Mining-services-glass-food, (h) Textile, (i) Textile-electrotechnics-ceramic, (j) Chemistry-mining, (k) Machinery-wood
Alker et al., 2000b	Brownfield sites	To develop a classification scheme and typology of brownfield which stakeholders will accept	United Kingdom	Definition of brownfield and redevelopment potential	(a) Vacant, available for immediate use, (b) Vacant, partially occupied or utilised, available for immediate use, (c) Vacant, requiring intervention, (d) Derelict, requiring intervention, (e) Contaminated, requiring intervention, (f) Vacant and Derelict, requiring intervention, (g) Vacant and Contaminated, requiring intervention, (h) Vacant, Derelict and Contaminated, requiring intervention, (i) Derelict and Contaminated, requiring intervention, (j) Vacant, partially occupied or utilised, requiring intervention, (k) Derelict, partially occupied or utilised, requiring intervention, (l) Contaminated, partially occupied or utilised, requiring intervention, (m) Vacant and Derelict, partially occupied or utilised, requiring intervention, (n) Vacant and Contaminated, partially occupied or utilised, requiring intervention, (o) Vacant, Derelict and Contaminated, partially occupied or utilised, requiring intervention, (p)Derelict and Contaminated, partially occupied or utilised, requiring intervention
Kim et al., 2018	Urban vacant land	To develop a typology that will support a better appreciation and understanding of the potential benefits of vacant land	Roanoke, Virginia, U.S.	Land use	(a) Post-industrial sites, (b) Derelict sites, (c) Unattended with vegetation sites, (d) Natural sites, (e) Transportation-related sites
Kremer et al., 2013	Vacant lots	To identify ecological landcover and uses of urban vacant lots for the planning of urban vacant lots	New York City, U.S.	Land use	(a) Unused land, (b) Private house, (c) Commercial\industrial, (d) Community garden, (e) Park, (f) Tree cover in residential street, (g) Sport fields, (h) Road, roadside pavement or sidewalk, (i) Junk yard, (j) Parking lot, (k) Non-commercial parking, (l) Other
Mathey et al., 2015	Green urban brownfields	To address the potential of green urban brownfields in providing ecosystem services in urban areas	Germany	Successional stage of vegetation	(a) Brownfield with pioneer vegetation, (b) Brownfield with persistent ruderal vegetation, (c) Brownfield with ruderal tall herbaceous vegetation, (d) Brownfield with spontaneous wood
Moser et al., 2015	Vacant urban areas	To identify and monitor vacant and abandoned areas in large urban zones	Europe	Land use	(a) Greenfields, (b) Vacant or underused land, (c) Gaps in built-up areas, (d) Brownfields
Northam, 1971	Vacant urban land	To determine the approximate amount, monetary value, and proportion of buildable vacant urban land	U.S.	Redevelopment potential and barriers to it	(a) Remnant parcel, (b) Unbuildable, (c) Corporate reserve, (d) Held for speculation, (e) Institutional reserve
Rupprecht & Byrne, 2014	Informal green space	To determine how land use characteristics of Informal green space in two cities compare.	Brisbane, Australia and Sapporo, Japan	Land use	(a) Street verges, (b) Lots, (c) Gap, (d) Railway, (e) Brownfields, (f) Waterside, (g) Structural, (h) Microsite, (i) Power line

2.6 Conclusion

It has been shown that urbanisation can often result in pressure to redevelop brownfield sites for residential purposes (known as "Brownfield First") in order to preserve the greenbelt (Dallimer et al., 2011; Ministry of Housing Communities and Local Government, 2019b). Urbanisation can result in greater environmental hazard exposure to an increasing number of citizens, including those more socially and economically vulnerable (Romero Lankao & Qin, 2011). Simultaneously, the installation of and access to green space or infrastructure for these residents, and exposure to environmental hazards, is not equitable (Cutter et al., 2003; Wolch et al., 2014). Urban resilience is an important factor in the ability of cities to withstand these pressures and nature-based solutions are gaining popularity (Meerow & Newell, 2019). This is because they provide multiple ecosystem services reducing exposure to environmental hazards and increase access to green spaces and infrastructure (Staddon et al., 2018). The extent, location and physical state of brownfields has recently been identified as being potentially beneficial to urban areas, though the extent of this is little understood (Mathey et al., 2015). Discussion of these themes emphasise the need to investigate how brownfield ecosystem services contribute to urban resilience before they are redeveloped and understand the impacts of rapid land use/cover change on these little understood spaces.

The process of identifying and characterising brownfield, to establish their physical state and spatial distribution, are research challenges that continue to hinder the investigation of brownfield ecosystem service potential in relation to urban resilience challenges. Current approaches limit this by representing brownfield as an urban hazard, or a single entity, and undertaking site specific, and site scale analyses. The need for an assessment approach to establish the socio-ecological benefits of brownfield which is transferable and applicable at the city scale is essential. This would have wider implications for urban environmental research by contributing to existing knowledge in the fields of urban ecosystem service provision, and green infrastructure, which currently focus on formal urban green infrastructure. This would also contribute useful information for planners, surveyors, and local authorities. It could inform sustainable planning and management of brownfields, to advise on the effective use of brownfield, better support strategic redevelopment practices, and prevent loss of urban ecosystem services in areas where environmental inequity exists.

Chapter 3: Characterising brownfield

3.1 Introduction

In post-industrial cities around the world, de-industrialisation, demographic decline, and suburbanisation (population movement) processes have commonly led to an increase in urban brownfield sites (Martinez-Fernandez et al., 2012; Hollander et al., 2010). Recently, given limited space for development and the need for urban renewal and regeneration, many cities have implemented policies to redevelop brownfield, thereby limiting urban sprawl and protecting rural and green land (Dallimer et al., 2011). Urban densification through the redevelopment of brownfield sites has resulted in rapid and extensive land use and land cover changes, thereby altering urban structure with potentially significant impacts on the wider urban environment (Oke, 2002; Schulze Bäing & Wong, 2012). Over the past few decades, urban adaptation, and resilience in response to climate change and environmental hazards has become a pressing issue, along with the requirement to adopt sustainable land use strategies (Chen et al., 2009). To achieve this may require a review of planning policy regarding brownfield redevelopment to avoid potentially counteractive impacts.

As discussed in **Section 2.5.1** many varying and overlapping definitions and terms for brownfield exist globally. Furthermore, terms used to describe brownfield include wasteland, vacant land, derelict land, wildscape, drosscape, and vacant lots (Bonthoux et al., 2014; Kim et al., 2018). These different terms consider brownfield as a single type, based on perceived land use, and many carry negative connotations of unsafe or barren spaces of little ecological value. However, as research over the past few decades has shown, brownfield often comprises a diverse combination of land cover types, featuring pervious surfaces, vegetated areas at various stages of succession, and water bodies, alongside the built structures and impervious surfaces typically imagined as relics of past development (Gilbert, 1995). These varied land cover characteristics can play a key role in the provision of ecosystem services (Bolund & Hunhammar, 1999; Francis & Chadwick, 2013).

Currently, while Open Mosaic Habitats on previously developed land are included in the UK Biodiversity Action Plan (see discussion in **Section 2.4**), UK planning policy does not otherwise consider the actual or potential value of ecosystem services provided by brownfield sites. In the UK there is currently a focus on brownfield-first redevelopment to aid sustainable urbanisation and reduce urban sprawl. Redevelopment of brownfield will thus likely replace pervious and vegetated areas with built-up land, thereby resulting in the unintended consequence of reducing provision of ecosystem services and urban resilience to environmental hazards. It is therefore particularly important to better understand the complete stock of brownfield in cities, and their character, in order to identify their potential contribution to ecosystem services and urban resilience before they are lost to development. As a first step, this requires the identification of brownfield sites across a city and a broadly applicable brownfield typology that encompasses site conditions and indicates current and potential physical state and urban ecosystem service benefits.

3.1.1 Brownfield classification and typologies

Previous work has explored brownfield character through classifications and typologies for various and specific motivations, often identifying brownfield as a single type in a broader typology. For example, brownfield may be identified as a single entity within a wider typology of urban land uses or may be incorporated within a typology of unused spaces. Many unused or vacant land typologies can often contain land which is incidental (left over land from previous developments) or previously undeveloped such as, railway sidings, road verges, riverbanks (vacant areas not considered for development, but with no formal use) (Kim et al., 2018; Rupprecht & Byrne, 2014). More brownfield specific typologies have typically focussed on remediation and economic goals and often utilise indicators of land use rather than those that identify physical status. Such approaches do not fully consider the diverse nature of brownfields (Kim et al., 2018; Rupprecht & Byrne, 2014).

Due to misconceptions caused by conflicting definitions and terms, brownfields are often perceived as negatively impacting local communities and the environment (Kim et al., 2018). Viewed through this lens, brownfield redevelopment equates to reducing harms, and many classifications have focused on identifying suitability or priority for redevelopment based on remediation time and financial or economic factors (Alker et al., 2000b; Dasgupta & Tam, 2009). Whilst today's sustainable redevelopment practices seek to deliver economic, social and environmental enhancements, the environmental improvements are largely focussed on harm reduction through contamination remediation and reducing perceived negative health impacts (Pizzol et al., 2016; Rizzo et al., 2015).

Recently, some research has begun to incorporate socio-ecological aspects such as community use or ecosystem benefits into typologies (of vacant land) as the realisation that previously developed land can present social, ecological and environmental benefits within urban areas is increasingly acknowledged (Kremer et al., 2013; Mathey et al., 2015). While this is an important advancement, to date many of these typologies are represented by somewhat broad groupings/terminology, for example 'post-industrial' or 'vegetated' types, within which brownfield sites with wide ranging physical and ecological states may be grouped. Moreover, the spatial patterns and distribution of these brownfield typologies is rarely considered, which is important to address how any brownfield benefits are related to the urban system.

In summary, brownfield classifications are generally based on specific site-based attributes related to stakeholder interests and redevelopment potential (cost, contamination, location), and may employ contextual descriptors (neighbouring land uses or socio-economic aspects). These can be variably defined and applied depending on stakeholder objectives and site location, a problem exacerbated by the varying definitions and understandings of brownfield itself (Dasgupta & Tam, 2009). The misrepresentation of brownfields as a single entity, which have several conflicting terms and definitions can lead to uninformed, disproportionate, and extensive redevelopment of brownfields sites, which is seen in many post-industrial cities. At the same time recent research is realising the potential social, environmental, and ecological benefits of brownfield for urban areas.

3.1.2 Criteria for a transferable classification of brownfield

To address this, typological exploration of brownfield should include site-level attributes that can be transferable and easily assessed to provide a comprehensive and inclusive typology of brownfield sites (Kremer et al., 2013). The most useful attributes are those which can be broadly applied and readily evaluated at a conurbation scale, that provide relevant information regarding both redevelopment potential, and current and future value of the site as green infrastructure and ecosystem service provision. Common site-based attributes that can be applied to any urban land parcel include size, topography, shape, and land cover, which according to Kremer et al. (2013) may allow strategic re-use of brownfield whilst supporting urban sustainability and resilience. Moreover, these criteria should allow city-scale analysis of brownfield due to their high transferability.

Land cover characteristics (and changes to them) have a significant impact on the surrounding environment (Oke, 2002), and are a key driver in ecological and ecosystem functions (Foley et al., 2005). As such, the measurement of land cover characteristics is essential for environmental modelling, monitoring, resource management, and planning (Vargo, Habeeb, & Stone, 2013). In previous typologies, including or based on brownfield, scrutiny of land cover has been undertaken as a method of site identification, urban land use change monitoring (Moser et al., 2015), or the creation of typology based on land use rather than physical status (Kim et al., 2018; Kremer et al., 2013). However, these studies, as discussed, tend to group brownfield into one land use category or into broad groups within which individual sites potentially have wide ranging physical conditions. Brownfield land cover has also been identified as an indicator of ecosystem services provision (Mathey et al., 2015), successional age (Schadek et al., 2009), and their redevelopment potential (Chrysochoou et al., 2012). In other studies the inclusion of land cover characteristics has also allowed assessments to be made with regard to the feasibility of short-term and long-term uses in terms of site safety, accessibility (Rall & Haase, 2011), and provision of open space for future use (Kim, 2018). Several brownfield studies have been undertaken at the site scale, though their application at a city scale is lacking. However, there has not been a city scale examination of land cover encompassing the complete stock of brownfields individually.

Alongside land cover, three physical characteristics of brownfield sites are particularly important in determining both development potential and possible ecosystem service benefits, namely site size, shape, and topography. Smaller sites are challenging to develop depending on the scale of operation. For example, single residential developments tend to be 20-30m wide and urban development's require a minimum 20m between blocks, which equates to a block depth of 40 to 50m, with a further requirement for a setback from transport infrastructure (Rudlin & Falk, 2009). Pagano and Bowman (2004) found site size to be the most common deterrent to redevelopment in US cities, whilst in the UK brownfields are required to be a minimum of 0.25ha or allow construction of five dwellings to be included on registers (Ministry of Housing Communities & Local Government, 2017). Small size often requires developers to acquire multiple sites, or construct more concentrated developments (Tiesdell & Adams, 2004).

In terms of barriers to redevelopment, for all but the most creative of designs, a small site area and highly irregular shape can be problematic, affecting the requirements and configurations of developments. Small and irregular shapes will constrict the length or width of a site requiring adaptation of a developments footprint and possibly bespoke plans (Rudlin & Falk, 2009). Pagano and Bowman (2004) found site shape irregularity to be the second most prevalent deterrent for redevelopment. Small irregularly shaped sites may, however, present important opportunities to enhance green infrastructure and habitat connectivity (if vegetated) (Kremer et al., 2013; Miyawaki, 1998), and have a direct positive relationship to the species richness of a site (Gonzalez et al., 2010). Though biodiversity (Bonthoux et al., 2014) and public perceptions of and willingness to use a locality can increase with size (depending on vegetative state) (Rall & Haase, 2011). These undisturbed brownfields can succumb to vegetation succession and urban woodland generation (Francis & Chadwick, 2013). As well as discouraging site disturbance, site shape can be an important indicator for biodiversity and landscape ecology due to the edge effect concept and greater perimeter of irregular shapes (Forman & Godron, 1981). Variances in the structure and population of vegetation and fauna occur at a site boundary due to differences in environmental conditions (Francis & Chadwick, 2013). Factors such as increased exposure light, wind, human interaction, pollution, and seed deposition, which can create niche habitats and edge tolerant species can become dominant (Francis & Chadwick, 2013).

Uneven, or overly steep topography is also a key aspect deliberated when assigning redevelopment projects to a specific area of brownfield, and this can increase redevelopment costs (Nogués & Arroyo, 2016). Consequently, slope has widely been considered a key barrier to redevelopment of brownfield (Kim et al., 2018; Northam, 1971; Pagano & Bowman, 2004). Nogués and Arroyo (2016) report slope thresholds for redevelopment as; recreational areas: no slope limit; conventional developments and general urban uses: 15%; roads, 10%; motorways: 5%, railways: 3%; and sewage networks: 5%. However, the reduced motivation to build, and reduced management regimes compared to more level surfaces, means that slope can be a positive indicator of tree canopy cover and green space quality (Davies et al., 2008).

Given the conflicting definitions of brownfield, an efficient and transferable typology should be based on elements that exist on brownfield whatever their local designation. This study focused on identifying and characterising brownfield to explore their physical features, spatial distribution in urban areas. The development of methods that enable a remote assessment of brownfield typology with a case study of Greater Manchester, UK was undertaken. Statistical methods were applied to a range of geospatial datasets to understand the structure, patterns, and relationships between the characteristics of brownfield typologies.

3.1.3 Chapter aim and structure

The aim of this chapter was **to characterise brownfield land, including consideration of spatial land use and land cover characteristics, and distribution across the urban environment**. This chapter is structured as follows. **Section 3.2** presents the methods, including creation of a spatial database of brownfield (**Section 3.2.1**), landscape and land cover analysis (**Section 3.2.2**), and creation of a typology of brownfield (**Section 3.2.3**). The results of the analysis are then described in **Section 3.3**. Finally, **Section 3.4** discusses the key findings, and identifies some limitations to the study.

3.2 Methods

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 spatial database of brownfield, **(ii)** the quantification of land cover and landscape metrics for all brownfield in Greater Manchester, **(iii)** the creation of a transferable typology of brownfield, and **(iv)** the analysis of the distribution of brownfields in urban, suburban and peri-urban zones. All spatial processing and analysis was carried out using Esri's © ArcMap 10.6 and statistical analysis undertaken in SPSS version 25.

To characterise brownfield land, including consideration of spatial land use and land cover characteristics, and distribution across the urban environment, a multi-step quantitative methodology was undertaken:

- Overlay analysis and interpretation of aerial imagery and topographic datasets were used to create a composite brownfield geospatial database utilising current and past brownfield databases.
- The quantification of brownfield land cover was undertaken using object-based image analysis, supervised land cover classification and the integration of topographic datasets.
- Spatial analysis tools and digital terrain models were utilised to analyse brownfield landscape metrics including size, shape, and slope.
- The construction of a brownfield typology was undertaken by employing k-means cluster analysis.

Mapping of the brownfields across the urban matrix utilises a reclassified land cover dataset and geospatial analysis.

3.2.1 Creating a brownfield spatial database

The first step was to create a novel augmented spatial database of brownfield, based on past and present brownfield register data, which is more comprehensive than recently released criteria-based registers in the study area. The most recent brownfield registers in England, available from the Ministry of Housing Communities & Local Government (2017), only include sites larger than 0.25 hectares where residential development is achievable. Earlier registers were therefore also attained from the 2010-2012 National Land Use Database of Previously

Developed Land (NLUD-PDL) (HCA, 2014). The spatial database was created by digitising the Greater Manchester 2017 brownfield register point locations using OS Mastermap topography layers (Ordnance Survey, 2017), and combining this with the 2010-2012 NLUD-PDL using overlay analysis. To identify any brownfield sites that had been developed in the period 2010-2017, Ordnance Survey Mastermap Topographic layers from October 2010 and December 2017 were utilised in conjunction with aerial imagery (Esri, 2017; Getmapping, 2018) in ArcGIS 10.6, to assess site changes, and developed sites were removed from the database.

3.2.2 Landscape metrics and land cover

The characterisation of Greater Manchester brownfield was based on landscape metrics (size, shape, and slope) in combination with land cover characterisation, where the use of widely accessible criteria enables transferability of the method. These criteria are typically seen as key indicators for ecology (Uuemaa, Mander, & Marja, 2013), ecosystem services (Syrbe & Walz, 2012), sustainable planning and development (Horning, 2008), and conventionally, constraints to development (Pagano & Bowman, 2000). Site size in hectares 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). Mean slope was calculated using the Ordnance Survey Terrain 5 digital terrain model dataset (5m spatial resolution) (Ordnance Survey, 2018b). The data set was clipped to each brownfield boundary and slope statistics calculated using the ArcGIS zonal statistics tool. Descriptions of each metric are presented in Table 3.1.

Table 3.1: A brief description of each measured metric used to create the brownfield typology.

Variable	Description
Size/area (ha)	The area of each brownfield site measured in hectares.
Grass %	Percentage of site area comprised of grass for each brownfield site.
Trees, shrubs, bushes %	Percentage of area comprised of trees, shrubs, or bushes for each brownfield site.
Bare earth %	Percentage of area comprised of bare earth for each brownfield site.
Hard surface %	Percentage of area comprised of hard surfaces (i.e. concrete/tarmac) for each brownfield site.
Built structure %	Percentage of area comprising of a built structure for each brownfield site.
Water %	Percentage of area comprising of water for each brownfield site.
Total vegetated %	Percentage of brownfield site that is vegetated, comprising of the sum percentage cover of both grass and, tree, shrub, bushes.
Total impervious surface %	Percentage of brownfield site that is impervious, comprising of the sum percentage cover of both hard surfaces and built structures.
Total pervious surface %	Percentage of brownfield site that is pervious, comprising of the sum percentage cover of vegetated surface, bare earth, and water cover.
Slope mean (degrees)	The mean slope in degrees. The mean of all slope measurements ($5m^2$) for each brownfield site.
Perimeter-area ratio (PAR)	The ratio of the perimeter to the area of a shape is the perimeter (m) divided by the area (m^2). The perimeter of each brownfield site is the measure of the length around the site boundary. The area of the brownfield site is the amount of two-dimensional space within the perimeter.
Area Weighted Mean Shape Index (AWMSI) (Compactness, regular, irregular)	Equals the sum of each brownfield site perimeter, divided by the square root of patch area (in hectares) for each brownfield site and adjusted for circular standard. It Is weighted by patch area, so larger patches will weigh more than smaller ones.
Mean Patch Fractal Dimension (MPFD) (Shape complexity)	Mean patch fractal dimension (MPFD) is a measure of shape complexity. Mean fractal dimension approaches one for shapes with simple perimeters and approaches two when shapes are more complex.

High resolution (25cm) orthorectified colour aerial imagery, in 1km^2 tiles, with image capture dates ranging from 2009-2016, was obtained from Getmapping Aerial Photography Data Collection through the Aerial Digimap service (Getmapping, 2018). 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, shrubs, and bushes; grass and herbaceous vegetation; bare earth; water bodies; impervious surfaces; built structures, and shadow (shaded areas where land cover cannot be identified). The MLC was calibrated to take into consideration shape, size, colour, rectangularity, compactness, 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). To minimise misclassifications and thus improve classification performance, the classified images were amalgamated with ancillary data (Lu & Weng, 2007), with the use of 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. A workflow of the land cover classification process is presented in Figure 3.1. Accuracy assessment was then facilitated by validating 1200 sample points using the high-resolution imagery to create a confusion matrix indicating accuracy for each land cover class.

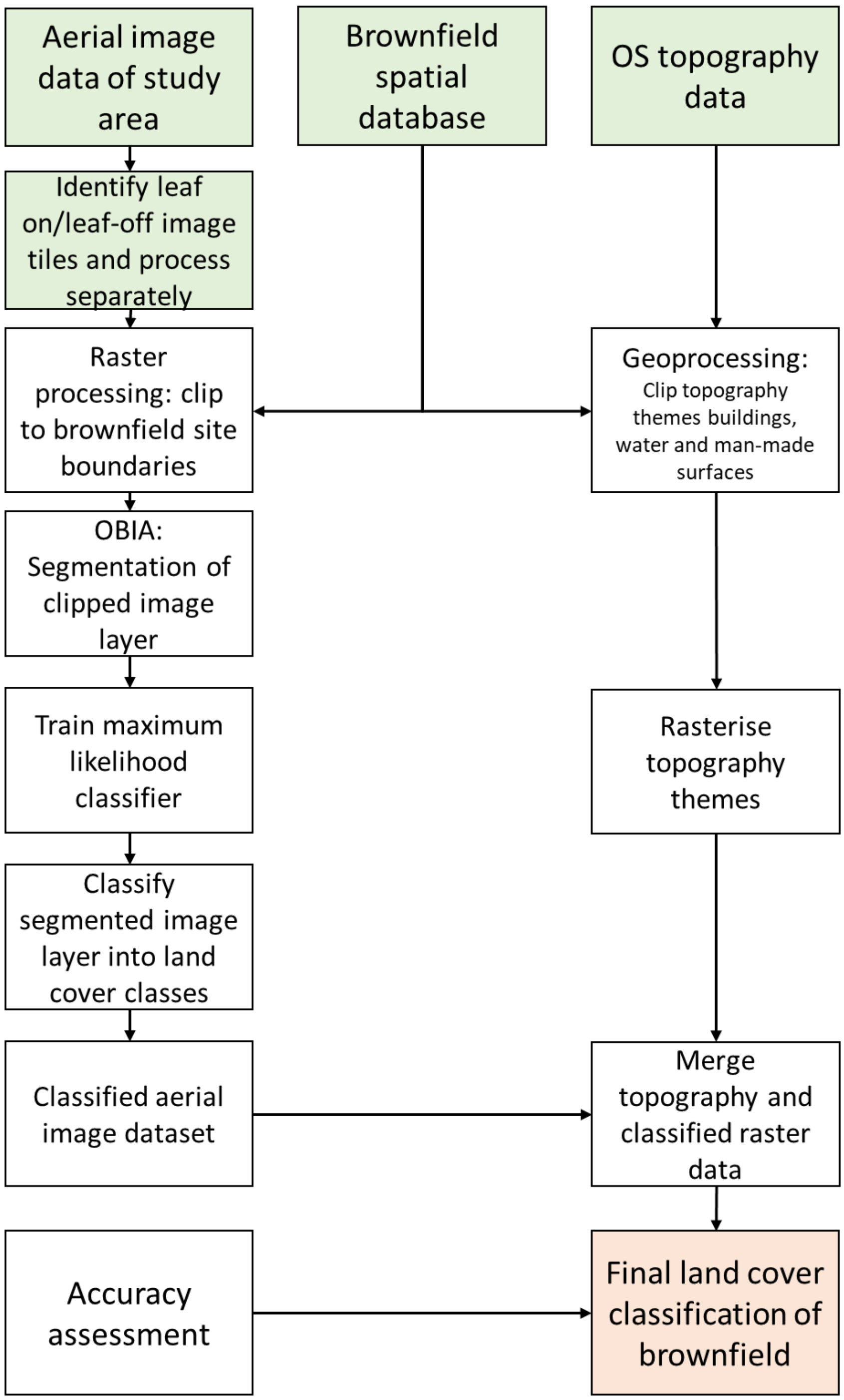


Figure 3.1: Workflow of brownfield land cover classification.

3.2.3 Creation of a brownfield typology

The brownfield typology was based on a hierarchical classification produced using sequential applications of the k-means clustering algorithm [cf. Vickers and Rees (2007)] in IBM SPSS Statistics for Windows, Version 26.0. K-means cluster analysis has been effectively used in urban typological research (Dennis et al., 2018; Gil, Beirão, Montenegro, & Duarte, 2012; Huang, Lu, & Sellers, 2007) and geodemographic studies (Harris, Sleight, & Webber, 2005; Vickers & Rees, 2007). This iterative method attempts to form clusters or groups, whilst minimising the variability within each cluster and maximising the variability between clusters (Frey, 2018).

The brownfield criteria input into the clustering algorithm were percentage land cover (for the six land cover classes, alongside percentage vegetated and impervious), and the landscape metrics described above (Table 3.1). Due to the different measurement scales of the input variables, data was standardised using z-scores prior to k-means clustering (Mohamad & Usman, 2013). The data set was initially analysed from a starting point of 2 to 10 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 several cluster solutions performed well on both assessments, the solution with fewer clusters was chosen (Frey, 2018).

The distinctiveness of emerging groups were evaluated both quantitatively using ANOSIM from the PAST statistics package (Hammer, 2019), and qualitatively by visually examining high resolution aerial imagery (ESRI, 2017) and one of three actions taken. First, clusters with high dissimilarity and clear visual differences (to all other clusters) were identified as a distinct brownfield type. Second, clusters with low dissimilarity (to each other) and visual ambiguity (visual inspection of aerial images did not identify qualitative differences between the clusters) were merged to form a single brownfield type. Finally, where visual inspection of large groups ($n > 50\%$ mean cluster membership e.g. initial sites/optimal cluster solution (Vickers & Rees, 2007)) indicated qualitative differences between sites, the sub-set of site data was separated out and re-passed through the full clustering process. A workflow for the k-means clustering process is presented in **Appendix 3.1**. A three-level 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 level 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.

3.2.4 Mapping the brownfield typology

The geographical distribution of the brownfield typology was assessed using a reclassified 2015 vector land cover map for the U.K. (LCM2015), released in April 2017 (Rowland et al., 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 (Collin, 2004) resulting in a three-class land cover map for Greater Manchester. Spatial analysis of the brownfield typology, using point density analysis, based on polygon centroids, was undertaken to explore the distribution patterns of different brownfield types in Greater Manchester.

3.3 Results

3.3.1 Brownfield land scape metrics, land cover and distribution

The spatial distribution of Greater Manchester brownfield is presented in Figure 3.2, which shows urban, suburban, and peri-urban settings and brownfield distribution across them. A summary of the associated landscape metrics and land cover types presented in Table 3.2 and Figure 3.3 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 less than 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, greater than 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 greater than 15 degrees. Results from shape metrics emphasise the diverse brownfield geometry, from very compact to highly irregular and complex sites.

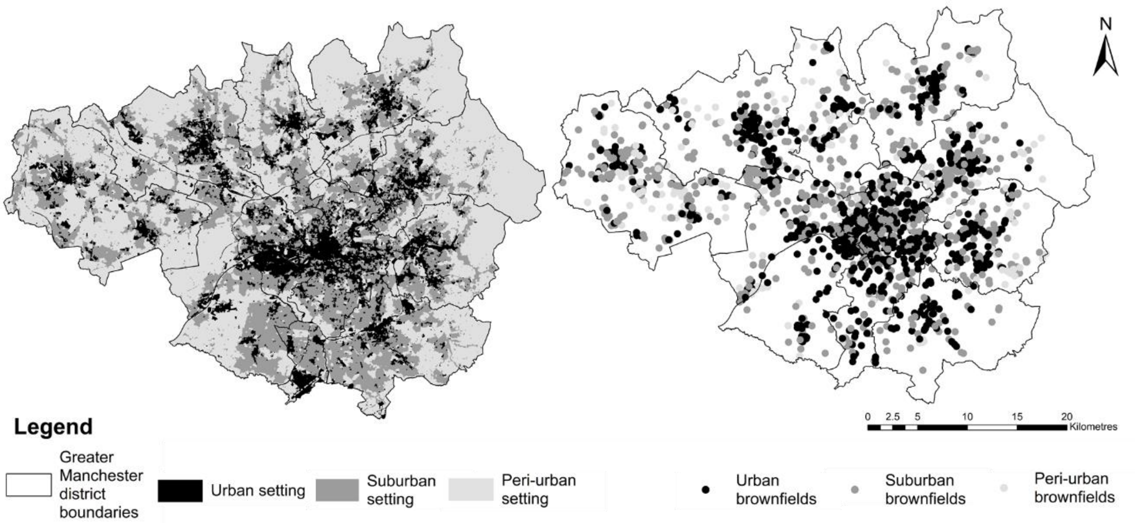


Figure 3.2: A spatial database of brownfield sites in Greater Manchester. Greater Manchester district boundary data, ONS (2018).

Table 3.2: Descriptive statistics for brownfield landscape metrics.

Metric	Statistic	Bolton	Bury	Manchester	Oldham	Rochdale	Salford	Stockport	Tameside	Trafford	Wigan	GM Total
No of sites	n	189	109	505	164	166	410	105	216	81	252	2197
Area (ha)	Sum	291.3	229.7	520.3	245.1	155.1	389.2	125.2	183.8	103.6	918.2	3161.6
	Min	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	76.7	28.0	71.7	42.2	14.3	57.0	16.1	19.0	28.8	268.3	268.3
	Mean	1.5	2.1	1.0	1.5	0.9	1.0	1.2	0.9	1.3	3.6	1.4
	Std. Dev	5.9	4.2	3.9	3.7	1.8	3.4	2.4	1.6	3.3	19.3	7.4
Slope	Min	0.2	0.2	0.2	0.0	0.3	0.1	0.2	0.4	0.1	0.2	0.0
(deg)	Max	17.5	21.6	17.0	25.4	13.6	15.0	24.8	19.2	4.2	14.0	25.4
	Mean	3.2	3.7	2.1	4.1	3.1	2.2	3.4	4.1	1.5	2.0	2.7
	Std. Dev	2.5	3.5	2.1	3.6	2.4	2.1	3.2	3.3	1.0	1.5	2.6
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	0.5	0.2	0.5	0.3	0.5	0.8	0.4	0.5	0.3	0.5	0.8
	Mean	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Std. Dev	0.1	0.0	0.1	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	3.2	2.4	3.3	3.3	3.7	10.2	2.5	3.7	3.9	6.0	10.2
	Mean	1.4	1.4	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
	Std. Dev	0.3	0.2	0.3	0.3	0.3	0.5	0.2	0.3	0.4	0.5	0.4
MPFD	Min	1.3	1.3	1.2	1.3	1.3	1.2	1.2	1.3	1.3	1.2	1.2
	Max	1.7	1.5	1.7	1.6	1.7	1.9	1.6	1.7	1.6	1.7	1.9
	Mean	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
	Std. Dev	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Land cover statistics for the 2,197 brownfield sites in Greater Manchester and districts are presented in Figure 3.3. Overall, 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 impervious land cover types include hard surfaces which cover 28.62%, and buildings accounting for 8.82%. Shadow obscuring true land cover is minimal in the classification (3.84%). Accuracy assessment indicated the OBIA and classification procedure was 94% accurate overall, above the widely cited satisfactory result of 85% for image classification (Foody, 2008; Thomlinson, Bolstad, & Cohen, 1999) and a confusion matrix is presented in Table 3.3.

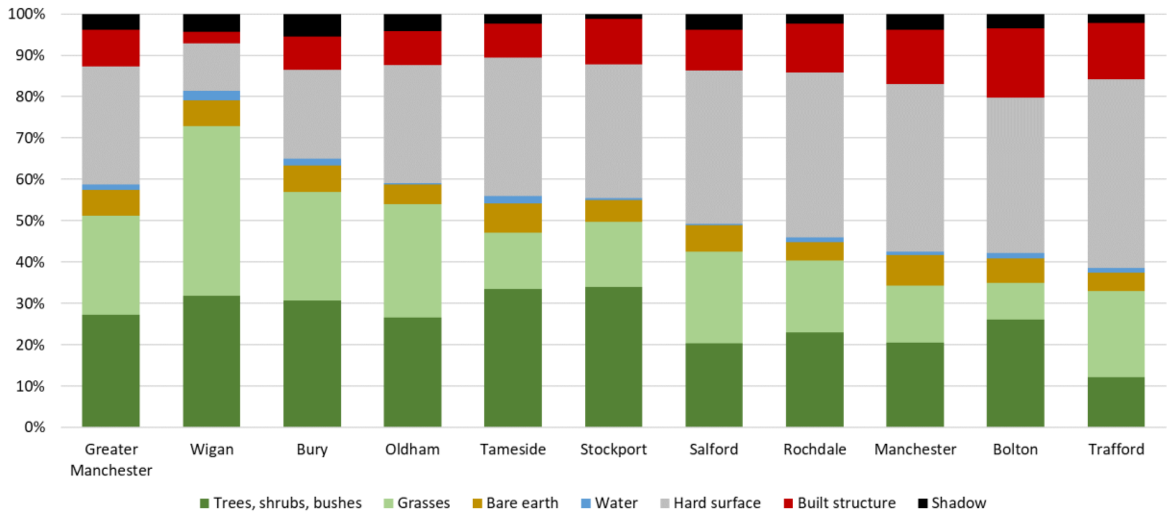


Figure 3.3: Land cover statistics for brownfield sites in Greater Manchester and districts.

Table 3.3: A confusion matrix presenting accuracy of brownfield land cover classification.

Class	Grass/herbaceous	Trees and shrubs	Bare earth	Hard surface	Built structure	Water	Shadow	Total	User Accuracy	Kappa
Grass/herbaceous	206	7	1	0	0	0	0	214	0.96	0
Trees and shrubs	17	270	0	2	2	0	4	295	0.92	0
Bare earth	2	1	58	13	0	0	0	74	0.78	0
Hard surface	10	4	7	393	0	0	1	415	0.95	0
Built structure	0	0	0	1	141	0	0	142	0.99	0
Water	0	0	0	0	0	12	0	12	1	0
Shadow	1	2	0	0	0	0	45	48	0.94	0
Total	236	284	66	409	143	12	50	1200	0	0
Producer Accuracy	0.87	0.95	0.88	0.96	0.99	1	0.9	0	0.94	0
Kappa	0	0	0	0	0	0	0	0	0	0.92

3.3.2 Brownfield typology

The three-level hierarchical typology identified twenty-six brownfield types distinguished by their land cover characteristics and contrasting or complex landscape metrics (Figure 3.4). Descriptions and examples of aerial imagery of the typology are presented in **Appendix 3.2 and 3.3**. Figure 3.4 presents the three-level hierarchy, landscape metrics, land cover of each type of brownfield at the third level of the typology. The typology's hierarchical organisation enables 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 level three types into subtypes if/where necessary.

The typology clearly divides brownfields into two distinct primary groups of predominantly impervious and predominantly pervious sites (Figure 3.4). Predominately impervious contians 1275 sites, with a total area of 1321ha. Predominately pervious group encompasses 922 brownfields exhibiting a total area of 1841ha. Predominantly pervious types exhibiting a significant land area are also seperated at the first level. Predominatly impervious level two clustering seems to be dominantly based on landcover type, distinguishing between sites dominated by built structures, hard standing, and sites with some vegetation. Sites with dominant structures break down at level three, to identify types (a) buildings and (b) compact commercial units, almost entirely dominated by built structures which are flat, compact and small sites. Level two hard surfaced group, breaks down into types with dominant hard standing, such as (c) impervious grey surfaces, and (d) industrial units and yards, which have expansive impervious surface cover, level topography, can be irregular in shape, and larger than those dominated by structures. The level two group, built with vegetation, tend to be sites with structures and hard surfaces where vegetation is present at the periphery such as (h) industrial with peripheral vegetation, or (i) hard surface with peripheral vegetation which exhibit a greater area, more uneven topography, and are less compact sites.

In comparison to the predominantly impervious sites, the level one predominantly pervious group breaks down into level two groups based on vegetation type, successional stage, and distinct landscape metrics e.g. vacant with successional vegetation, irregular and large, predominantly short vegetation, and highly vegetated. Sites with vacant successional vegetation break down at level three to identify types where evidence of previous man made structures or materials exist along side pioneer vegetation, for example (m) properties with mid-successional land or remnant gardens, and (n) site remnants and foundations with successional vegetation. These types can be uneven, irregularly shaped and small or large in area. Level two predominantly short vegetation, breaks down into types with dominant grassland areas, such as, (s) urban pioneer vegetation and amenity grassland, (t) scrub grassland, and (u) informal open grassland, which have expansive pervious surface cover, some uneven topography, irregular shape, and generally larger than impervious types. The level two group, highly vegetated, tend to be sites with high proportion of tree canopy cover such as (x) highly vegetated supplementary or enclosed sites, or (y) densely vegetated which tend to have a moderate area, uneven topography, and irregular shape.

The nature of the sites (h) to (l), originating in the predominantly impervious level one group, and types (m) to (o) stemming from the level one predominantly pervious group, display evidence of dereliction and early successional transition. The emphasises the transient nature of the typology where impervious sites, if left undeveloped, will likely transition from dominantly impervious to dominantly pervious and vegetated, especially where structures are demolished and hard surfaces disagregated. Brownfield that exhibit extensive hectarage or those containing a water body occur less frequently in Greater Manchester. Types containing a higher proportion of bare earth and consequently pervious surface are formed as two distinct types (types (l) and (q)), though the majority of brownfields contain bare earth to some extent. It is also clear that brownfield sites that have traditionally been perceived as difficult to develop, such as sites with uneven topography (type (o)), irregular shapes (type (p)), and those containing a water body (types (r) and (w)) (Hollander et al., 2010; Pagano & Bowman, 2004), display superior levels of pervious and highly vegetated land cover.

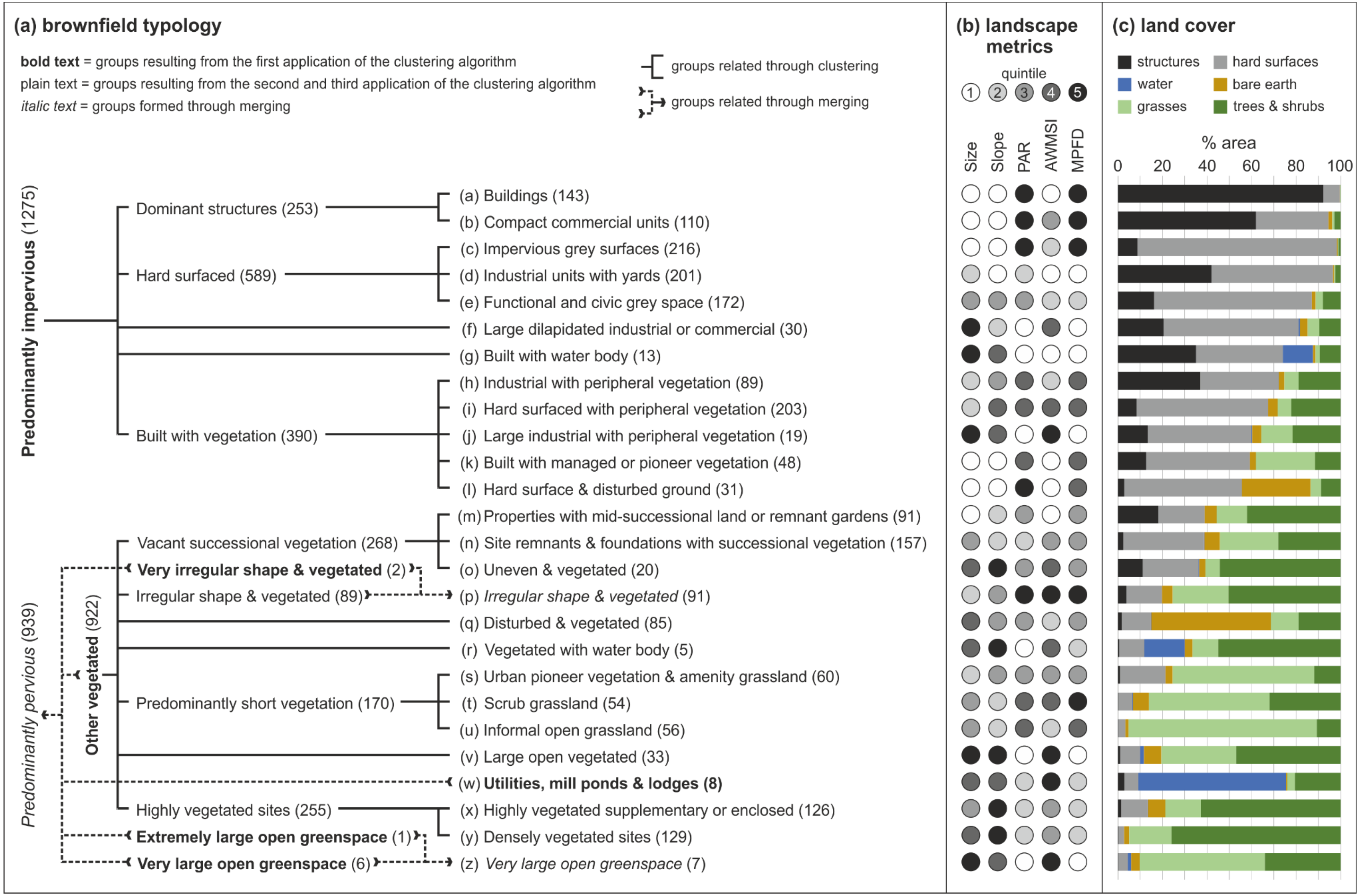


Figure 3.4: Brownfield hierarchical typology landscape and land cover metrics and urban distribution. The typology is presented in ranked order based on the proportion of impervious to pervious land cover types at Level 1, Level 2 and Level 3.

3.3.3 Distribution of brownfield typology across the urban environment

The general pattern of distribution emphasises the prominence of predominantly impervious types in urban areas, and predominantly pervious types present in suburban and peri-urban zones (Fig. 3.5 and 3.6). Four main groups with divergent spatial patterning are observed within the typology as a whole, examples of which are presented in Figure 3.6 and 3.7. For example, level three of the typology highlights how brownfields that contain high percentages of artificial structures or surfaces (e.g. types a to g) are typically highly clustered in urban areas and district centres with very low occurrence in peri-urban areas. Predominantly impervious types which contain moderate amounts of vegetation (e.g. types h to l) are less clustered in urban centres than significantly impervious types. Those exhibiting greater amounts of vegetation (e.g. types m to y, excluding v) are less clustered and more widely distributed, mainly across the suburban and peri-urban areas of the conurbation (Fig. 3.6 and 3.7). Very large open sites (z) are dominantly/nearly exclusively peri-urban in distribution. Examples of brownfield types within these four main groups of spatial patterning are presented in Figure 3.7.

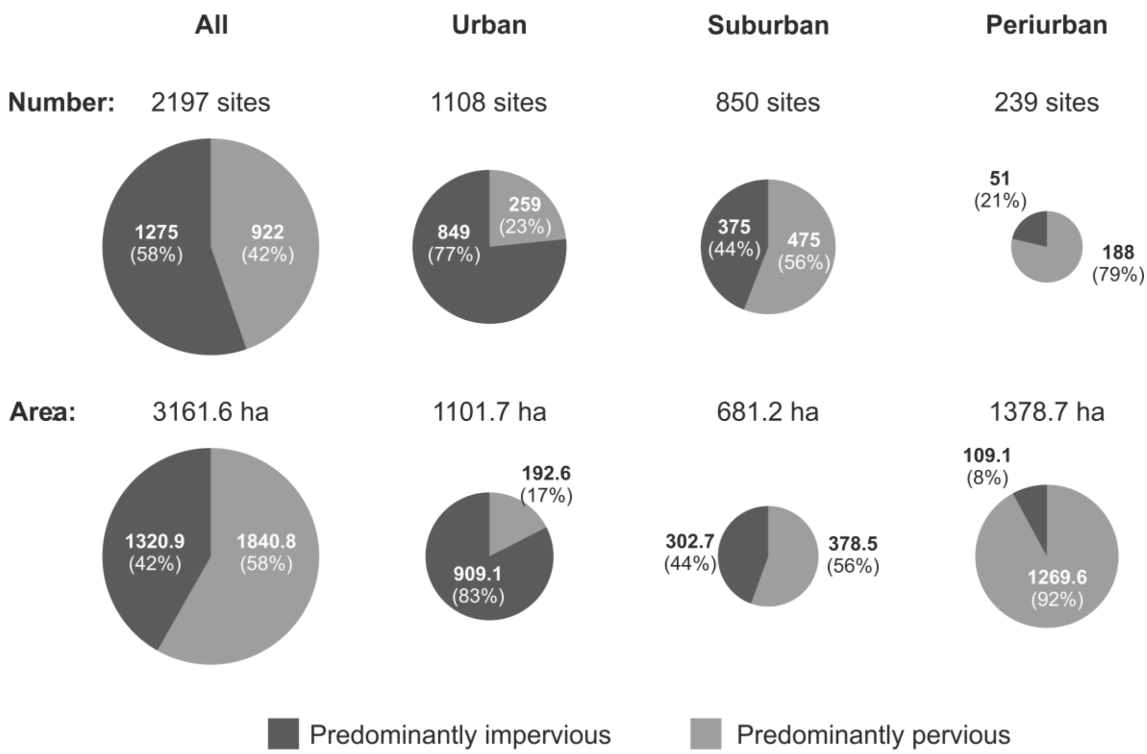


Figure 3.5 Urban distribution of level 1 of the hierarchical brownfield typology. Note: area of pies is proportional to number or area of brownfield sites.

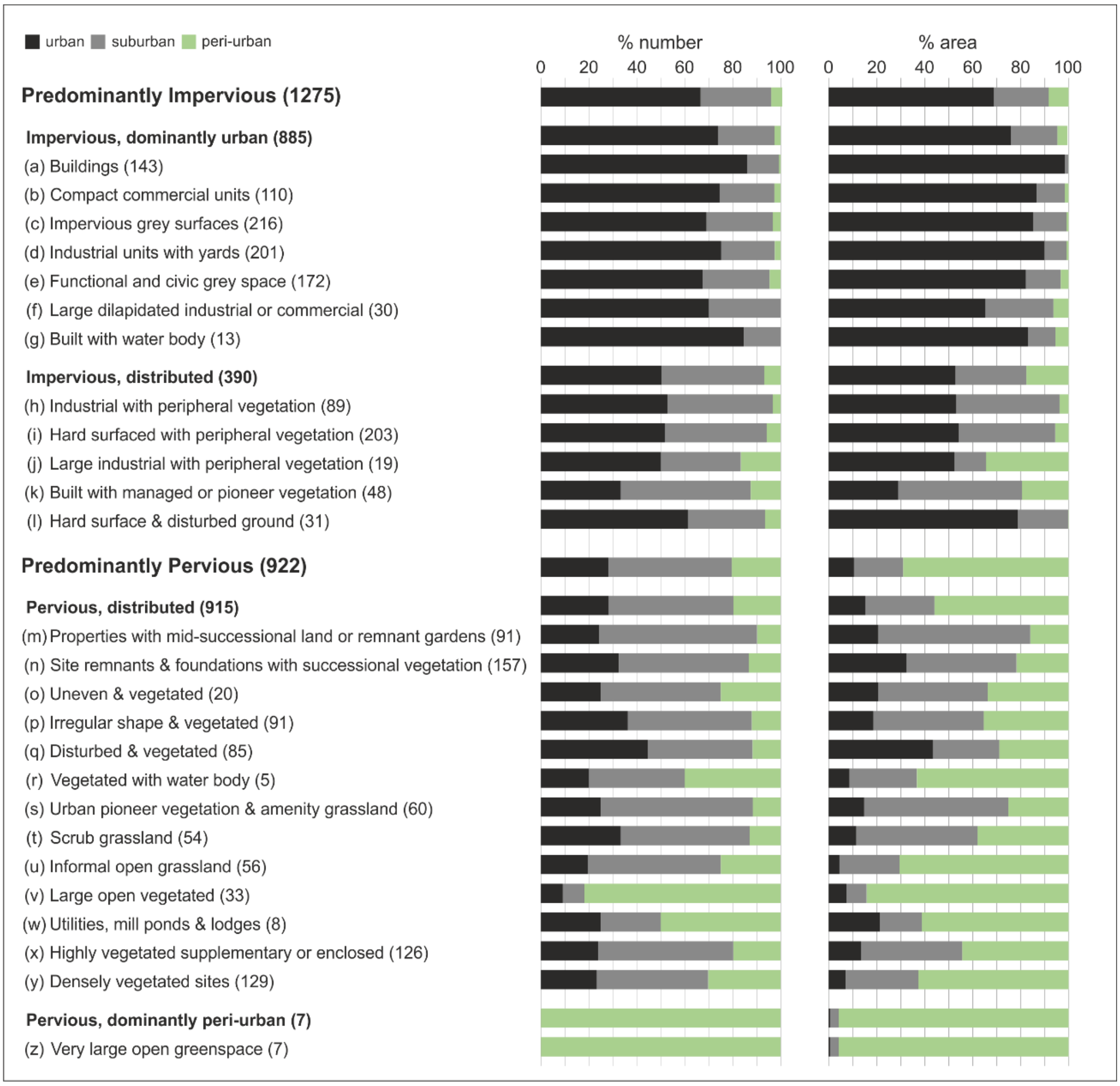


Figure 3.6: Typology distribution across urban, suburban, and peri-urban zones by percent number and area of sites. Note: Four patterns of distribution (1) impervious, dominantly urban, (2) impervious, distributed, (3) pervious and distributed, and (4) pervious and dominantly peri-urban.

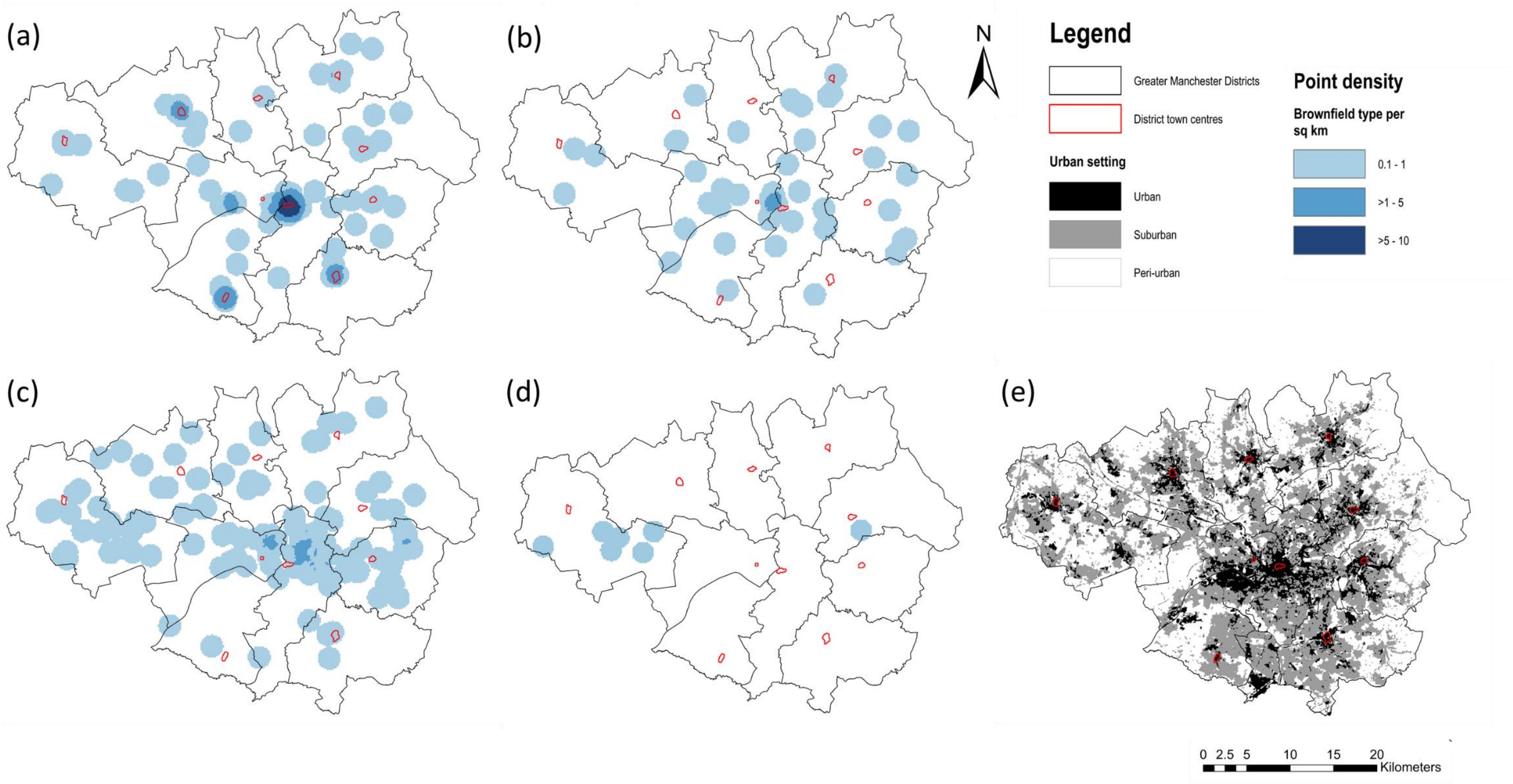


*Figure 3.7: Examples of divergent spatial patterning observed within the typology. Image **3.5a** represents type (a) Buildings, Image **3.5b** represents type (k) Built with managed or pioneer vegetation, Image **3.5c** represents type (y) Densely vegetated, Image **3.5d** represents type (z) Very large open green space, image 3.5e displays urban, suburban and peri-urbanzones 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 MHCLG (2020) no conditions apply.*

3.4 Discussion

This objective of this chapter was to characterise brownfield land, including consideration of spatial land use and land cover characteristics, and distribution across the urban environment. A three-level hierarchical typology identified twenty-six brownfield types distinguished by their land cover characteristics and contrasting or complex landscape metrics. The brownfield types display variations in terms of the proportion of impervious and pervious land cover and vegetation type/succession. Large, topographically challenging, and irregularly shaped sites are also distinguished. Many brownfield types were found to contain substantial pervious surface cover, including highly vegetated areas, bare earth, and water bodies which are distributed across the city. Conversely, several highly impervious brownfields are highly clustered in densely built up urban area. These results offer important insights into the potential of brownfield, with or without modification, to provide green infrastructure and associated benefits across a network of relatively unstudied areas. Furthermore, the typology identifies brownfields whose redevelopment would least impact any social-ecological benefits provided by the natural/semi-natural land cover components present, and conversely, those that may benefit from some green intervention, or indeed prove difficult to develop.

The quantity of vegetated and pervious land identified on Greater Manchester brownfields equals 1620 ha (trees and shrubs 27%, grass and herbaceous vegetation 24%, water 1%, and bare earth 6%), which have previously been unaccounted for in green audits of the study area, and are not included on existing green infrastructure maps (Greater Manchester Combined Authority, 2019b; The Environment Partnership, 2010). Hence, the typology and results suggest that many Greater Manchester brownfields are a dynamic resource and a valuable component of green infrastructure that potentially contribute significant ecosystem service benefits, provide land suitable for strategic greening and other interim uses to aid climate resilience. The identification and knowledge of the distribution of green infrastructure to enhance socio-ecological resilience is important especially at the city scale (Meerow & Newell, 2017). This can be useful for ensuring priority areas retain or enhance current green infrastructure, though current research tends to focus on traditional green spaces and infrastructure such as parks, green roofs, and street trees for example (Norton et al., 2015).

The overall distribution of brownfields identified within the Greater Manchester conurbation concurs with other studies, in that brownfields have a wide geographical distribution (Bambra et al., 2015), but are typically concentrated in built up urban areas, leading to disproportionate distribution (De Sousa, 2003). For example, Frantál et al. (2013) found that moving out of densely built-up areas less brownfield is evident, and that those present are often disused civic or community amenities and their associated grounds. Further afield, relatively few brownfield sites are located on the rural fringe. The distribution of all brownfield in Greater Manchester is 50% urban, 39% suburban, 11% peri-urban which is compatible with other studies, however, the distribution of individual types of brownfield provides an important resource which to the authors knowledge has not been investigated before.

The more detailed typology goes further revealing specific distribution patterns of brownfield types, such as buildings and impervious grey surfaces, which are significantly more prevalent in densely built up areas, whilst highly vegetated types are less clustered, and more evenly distributed across the urban, suburban, peri-urban domains. This emphasises the value of these densely vegetated brownfield in built-up urban areas, especially where brownfields are a target for redevelopment. This is important as inequalities in open and green spaces have been identified (Mitchell & Popham, 2007; Schüle, Gabriel, & Bolte, 2017a), and measures to increase green infrastructure to support urban resilience are employed in cities (Meerow & Newell, 2019). Simultaneously, unaccounted for, highly vegetated brownfield are likely being replaced. Alternatively, those areas with an excess of impervious brownfield and a lack of open or green space impart the importance of careful strategic selection for redevelopment, greening, or interim use of brownfield based on their characteristics and location, as supported by the typology presented here.

The spontaneously vegetated and pervious brownfields identified using the typology can indicate provision of important urban ecosystem services, such as air pollution removal, carbon sequestration, avoided surface water runoff (Kim, Miller, & Nowak, 2015), reduction in ambient air temperatures (Mathey et al., 2015), and increased urban biodiversity (Robinson & Lundholm, 2012). If pervious and vegetated brownfield types were permitted to develop mature canopy cover then the capacity to provide regulating ecosystem services would increase significantly. The current or potential contribution to urban resilience may, however, be lost when redevelopment commences, emphasising the usefulness of this method for informing strategic sustainable redevelopment, or the implications for green remediation procedures.

Another insight offered by the typology is the highly vegetated nature of difficult to develop, urban brownfields. One example of this are irregularly shaped and topographically challenging sites, which most likely have proven difficult to redevelop (or access) in the past (Pagano & Bowman, 2004), allowing natural succession to take hold (Gilbert, 1995). This highly vegetated condition makes sense, and Schadek et al. (2009) has linked vegetation structure to site age, as well as soil condition and species richness. Sites like these, with limited or more costly development potential (though still under increasing pressure to redevelop them), could provide opportunities for other alternative uses whilst retaining most of their current ecosystem services benefits (Healey-Brown, Jackson, & Wray, 2011). These sites would be suitable for use as greenways or pocket parks for example (Kremer et al., 2013). Some organisations such as Sustrans (overseers of the National Cycle Network in the UK) have managed areas such as these, creating cycle paths and tracks in urban areas (Sustrans, 2019).

The identification of a variety of pervious surfaces on brownfields can provide further information about site conditions, and insights into niche ecological, and ecosystem services provisioning in these areas (Robinson & Lundholm, 2012). Bare earth, which was identified on many brownfield types (and was a defining characteristic of types l and q), could inform the identification of potential OMH on brownfield, a habitat characterised by a mosaic of bare earth, herbaceous and scrub vegetation, and pools (Lush et al., 2013). Standing water bodies, although only identified in around 1% of brownfield sites, may offer several benefits. Ponds, including industrial related ponds are in decline in urban areas, and are often overlooked, and not included in the EU Water Framework Directive (2000/60/EC) (Hassall, 2014). However, small water bodies potentially provide several ecosystem services, including microclimate regulation, water regulation, pollution reduction (Haase, 2015), biodiversity, and habitat connectivity (Hassall, 2014).

In a planning context, the resulting typology has several potential applications which could be applied in practice which are discussed below. Applying the typology to initial site investigations may provide insight into potential hindrances to redevelopment (e.g. dense vegetation, water bodies, steep topography, unsuitable footprint, built structures or surfaces that require demolition or surface breakup work). The typology could be used to emphasise trade-offs with sites with lower provision of ecosystem services. For example, a highly vegetated site may offer potential benefits to urban areas with increased risk of exposure to environmental hazards, where the redevelopment of a nearby highly impervious and less productive site would not negatively impact local conditions. At present, in the absence of protected habitats, brownfield may be scraped clear of any vegetation, both as a land management strategy and in preparation for redevelopment (Hollander et al., 2010). Some redevelopment proposals assure the re-planting of trees in other areas to remediate any loss, however this may result in displacement of ecosystem services away from areas where there is Increased risk of exposure or high levels of vulnerability to environmental hazards.

Employing the typology using a temporal approach, utilising historical and/or future data, may provide insight into the life cycle of brownfields to inform maintenance routines or requirements. For example, how end-of use condition impacts upon the establishment and development of vegetation structure. Alternatively, temporal urban brownfield change is relatively unstudied in a socio-ecological context (Kattwinkel et al., 2011), and could inform about potential interim ecosystem services benefits to local communities. The typology also allows the identification of brownfield sites that would be suitable for temporary or interim opportunities for the public. These comprise level, open space, both pervious and impervious (i.e. 'impervious grey surfaces', 'hard surfaced with peripheral vegetation', 'informal open grassland'), which would require relatively little work to be put to productive use (Healey-Brown et al., 2011). These types of site, if not earmarked for immediate development, offer prime opportunities for temporary uses (Mathey et al., 2015). One example is urban agriculture or guerrilla gardening which can allow local communities to grow produce on both impervious and pervious brownfield transforming them for a positive function. Activities such as this offer several advantages to urban areas by improving urban sustainability, community benefits, and other ecosystem services (Hardman & Larkham, 2014).

3.5 Limitations

The methods used to generate the typology were effective for characterising brownfield, emphasising their diversity, and enabling specific types of brownfield to be identified, which can be useful for both indicating and detecting sites with socio-ecological benefits in specific urban zones. However, there were some limitations of the methods, first, the currency of the aerial imagery used for the land cover classification. Whilst the most up-to-date available was used, most of the imagery was captured in 2016, and a limited number of sites were from 2009. However, the inclusion of the latest topographic themes (from OS Mastermap topography data) for built structures, artificial surfaces and water bodies mean that these land cover classes are of reliable accuracy. Second, supervised classification relies upon image interpretation and accumulated knowledge of these areas, limiting use of the method by inexperienced analysts. However, the methods, datasets and software packages used to establish the typology are widely available and offer a highly transferable method of assessing brownfield sites at city, local or site scales, whatever the local designation or definition of brownfield. Furthermore, the application of this method to other urban scenes such as city blocks, parks, or neighbourhoods is possible. Third, the nature and rate of natural succession, or redevelopment, could mean that some brownfields currently contain different compositions of land cover classes, though the transitional and cyclical nature of brownfield abandonment, natural succession, management, and redevelopment mean the typology is still a relevant tool.

Chapter 4: Assessing brownfield ecosystem services

4.1 Introduction

Environmental hazard exposure impacts upon the residents, infrastructure, and plant and animal species in cities, and reducing these impacts has been the focus of urban adaptation and resilience strategies (Bowler et al., 2010; Gill et al., 2007). One nature-based solution for increasing urban resilience is the introduction of additional green infrastructure (urban greening) to enhance the provision of regulating ecosystem services and thereby reduce human exposure to environmental hazards (Bolund & Hunhammar, 1999; Staddon et al., 2018; Tzoulas et al., 2007). In practice, however, development often leads to the replacement of vegetated and pervious land cover with impervious artificial surfaces (Foley et al., 2005). In particular, urban brownfields represent a land use type that is rapidly and increasingly modified due to a focus on brownfield first redevelopment policies (Wong & Schulze Bäing, 2010).

Recent research has identified brownfield as vegetated spaces capable of providing several urban ecosystem services (Mathey et al., 2015; Robinson & Lundholm, 2012). However, these studies have focussed on recreational and cultural services (Mathey et al., 2015; Pueffel et al., 2018), biodiversity (Angold et al., 2006; Bonthoux et al., 2014), and less so, regulating ecosystem services, which have focussed on impacts to local microclimate (Koch et al., 2018; Mathey et al., 2015). Moreover, studies are typically conducted at a site scale, or considered brownfield as a single entity/land use type (see discussion in **Chapter 2, Section 2.4**), and to date there has been no comprehensive assessment of brownfield ecosystem service provision at a city-scale. Furthermore, there has been no direct comparison of brownfield to existing green infrastructure in terms of urban distribution and contribution to ecosystem service provision. This is a significant gap as while the drive to install addition green infrastructure in cities is intensifying, the synchronous loss of brownfield vegetation may result in unintentional net losses.

This chapter addresses these gaps, focusing on research Objective 2 **to assess the current provision of regulating ecosystem services of brownfield land, the potential if greened, and to compare this to existing urban green infrastructure**. Specifically, this research will evaluate climate, air quality, and flood regulation services provided by trees and tree canopy cover on brownfield and park land in Greater Manchester at both city and site-scale.

The unique characteristics of densely built urban areas can mean that some urban communities and inhabitants are at increased risk of exposure to environmental and climate hazards (Cutter et al., 2003; Cutter et al., 2009). Improving air quality and maintaining and/or reducing urban flood risk, and offsetting carbon to reduce atmospheric carbon dioxide are considered important factors in improving urban resilience (Meerow & Newell, 2019; UN-Habitat, 2020). Both climate and environmental hazards are projected to increase risk of exposure to urban residents (IPCC, 2014), especially those considered more vulnerable due to socio-economic and demographic inequalities (Cutter et al., 2003). This thesis specifically focuses on two environmental hazards that are important issues in urban areas: air pollution and flooding. In Greater Manchester, mitigating global climate change, improving air quality, maintaining and/or reducing urban flood risk are considered urgent environmental challenges and considered an important factor in improving urban resilience (Brisley et al., 2018; Clean Air Greater Manchester, 2020; Cox & Goggins, 2018; Greater Manchester Combined Authority, 2018, 2019a, 2019c).

Regulating ecosystem services include benefits resulting from the regulation and interaction with the movement and cycle of solids, gases, and liquids through the environment (Potschin & Haines-Young, 2016). Significantly, regulating ecosystem services ultimately help to reduce exposure to environmental hazards, and improve urban resilience (Bolund & Hunhammar, 1999; Demuzere et al., 2014; Gill et al., 2007; Nowak et al., 2007). In terms of ecosystem services, this thesis focuses on regulating ecosystem services, in particular carbon storage and sequestration, air pollution removal, including carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM_{10}, $PM_{2.5}$), and sulphur dioxide (SO_2), and the avoidance of surface water run-off at both city and site scales.

Significantly, trees deliver substantial regulating ecosystem services and filter air pollution, sequester and store carbon, whilst also reducing flood and storm water runoff, improving urban resilience (Bolund & Hunhammar, 1999; Demuzere et al., 2014; Gill et al., 2007; Nowak et al., 2007). Trees have been described as the principal and most noticeable components of green infrastructure and ecosystem service provision in urban areas (Bolund & Hunhammar, 1999; Elmqvist et al., 2016; Livesley et al., 2016). Trees provide a relatively significant proportion of regulating ecosystem services in comparison to other vegetation and natural/semi-natural land cover components (Bolund & Hunhammar, 1999; Davies et al., 2011b; Dobbs et al., 2011), and have been proven to promote urban adaptation and resilience to environmental hazards (Bolund & Hunhammar, 1999; Bowler et al., 2010; Elmqvist et al., 2016; Elmqvist et al., 2015).

In terms of regulating ecosystem services, trees are the most efficient form of biomass for carbon capture, and sequester carbon dioxide by fixing carbon during photosynthesis and storing it as additional biomass, both above and below ground (Nowak et al., 2013). Vegetation and leaf surfaces allow more dry deposition of air pollutants on their surfaces in comparison to many man-made surfaces such as glass, concrete, tarmac and other construction materials, which are free from complex irregularities, roughness, and projections (Hewitt et al., 2020; Wesely & Hicks, 2000). Gaseous air pollutants are also absorbed by leaf surfaces and leaf stomata (Nowak et al., 1998). Furthermore, trees capture and allow evaporation of significant amounts of precipitation, reducing and delaying surface accumulation and runoff (Bolund & Hunhammar, 1999). This research will focus on the regulating ecosystem services provided by trees and tree canopy cover on brownfields in Greater Manchester.

To understand the role of brownfield in supplying regulating ecosystem services, and to gain some perspective of this in relation to existing urban green infrastructure, parks will also be investigated. Parks are widely considered to contain high proportions of trees, and be instrumental as urban green infrastructure for providing regulating ecosystem services (Elmqvist et al., 2016; Francis & Chadwick, 2013; Wolch et al., 2014). Parks are some of the largest, abundant and widely distributed vegetated spaces within urban areas (Francis & Chadwick, 2013). The quantification of brownfield ecosystem service provision across Greater Manchester in urban, suburban, and peri-urban zones will therefore be placed in context by comparison to an urban park typology.

The spatial scale at which ecosystem services are modelled or mapped, for example air pollution and flood risk can be localised or regionally located (Kruse, 2017). However, regulating ecosystem services have been found to be most commonly mapped at larger national scale (Crossman et al., 2013; Egoh et al., 2012). However, site-scale assessments can help to understand localised ecosystem service provision and factors that affect them such as the composition and structure of trees (Nowak et al., 2008a). Undertaking both site and city-scale assessments can provide information for urban green infrastructure management and planning decisions, prioritising interventions and informing local policy (Nowak et al., 2008a), and identify how ecosystem service are distributed and where they are most beneficial based on locality and function.

This research thus addresses a significant gap in current understanding of ecosystem service provision by brownfield in urban areas before they are redeveloped. It presents the first quantitative city-scale spatial assessment of brownfield ecosystem service provision and enables the first direct comparison between ecosystem service provision from urban brownfield and parks. This new knowledge is critical to understand the value of brownfield in order to support ecosystem service monitoring, planning and management, as well as support strategic redevelopment to prevent loss of urban ecosystem services. For example, through the modification of brownfield types with few ecosystem benefits and retaining or enhancing brownfields with superior ecosystem service provision. It may also inform urban greening strategies for redevelopment plans, so that alternative decisions can be considered or like for like measures may be installed on new developments.

4.1.1 Chapter aim and structure

The aim of this chapter is **to assess the current provision of regulating ecosystem services of brownfield land, the potential if greened, and compare to existing urban green infrastructure**. The chapter is structured as follows: **Section 4.2** presents the methods, including the creation of a typology of urban parks, and the assessment of brownfield and park typology ecosystem services at both city-scale and site-scale, their urban distribution and potential if greened. The results of the analysis are then described in **Section 4.3**, including a typology of urban parks (**4.3.1**), regulating ecosystem service provision for brownfields and parks at a city scale (**4.3.2**), and their urban distribution (**4.3.3**), tree planting scenarios **(4.3.4)** before results of the site scale case study are presented (**4.3.4**). Finally, **Section 4.4** discusses the key findings, and before identifying limitations to the study in **Section 4.5**.

4.2 Methods

The following sections describe the methods used to undertake a city and site scale analysis and comparison of urban brownfield and park regulating ecosystem service provision in Greater Manchester. The characterisation of brownfields undertaken in **Chapter 3** created several datasets which will be utilised here, including the brownfield typology spatial datasets and reclassified UK land cover map, which identifies urban, suburban, and peri-urban zones (Rowland et al., 2017).

4.2.1 i-Tree ecosystem service modelling tools

Ecosystem service modelling and urban forestry analysis tools provided by i-Tree (https://www.itreetools.org), and developed by USDA Forest Service and numerous co-operators (Nowak, 2019) were selected to undertake this research. The i-Tree suite of tools was selected due to its focus on urban tree benefit analysis, the ability to assess multiple regulating ecosystem services, compatibility with the developed brownfield datasets, and the capacity to enable both remote city-scale (i-Tree Canopy), and physical site-based assessments (i-Tree eco).

The i-Tree Canopy tool enables the assessment of regulating ecosystem service provision by urban tree canopy, including modelling of carbon sequestration and storage, air pollution removal, and avoided surface water runoff. i-Tree Canopy has been widely used to estimate urban tree canopy and ecosystem service benefits in the U.S., Portugal, Australia, Italy and Ireland (Buccolieri et al., 2020; Del Moretto, Branca, & Colla, 2018; Hirabayashi, 2014; Mills et al., 2016; Olivatto, 2019), and in early 2021 was adapted for use in the UK through the incorporation of data from a network of air pollution monitors and weather stations, thereby providing greater accuracy in regional assessments (Henning, 2021; i-Tree, 2020b). A key benefit of i-Tree Canopy is that it is based upon manual assessment of aerial imagery and therefore invaluable for evaluating inaccessible areas, e.g. closed sites and areas of very dense vegetation (such as privately owned brownfield) (Graça et al., 2017). Due to manual user identification of tree/non tree classifications for each point it has also been recognised as more accurate for the identification of tree canopy cover than other supervised and unsupervised image classification methods (Endreny et al., 2017).

i-Tree Eco is designed to use field data collected from single trees and plot-based assessments to quantify tree composition, structure, and regulating ecosystem services down to site, strata, species and individual tree level (i-Tree, 2019b). Functional analyses include air pollution removal, carbon storage and sequestration, and avoided runoff of trees and shrubs (i-Tree, 2019b). i-Tree Eco has been adapted for several countries including the UK where multiple large scale i-Tree Eco analyses have been undertaken (City of Trees Manchester, 2018a; Rogers & Jaluzot, 2015; Rogers, Jarratt, & D., 2011; Rogers, Sarcre, Goodenough, & Doick, 2015), with the largest study to date being undertaken in Greater Manchester by City of Trees with more than 2500 plots (City of Trees Manchester, 2018a). Data from the City of Trees (2018a) study is used here to compare brownfield tree composition in other urban land uses in Greater Manchester.

4.2.2 City-scale datasets

The city scale i-Tree Canopy assessment provides a measurement of tree canopy cover on brownfield and parks within Greater Manchester. As with brownfields, parks are not assumed to be identical, and can vary depending on structural aspects, landscape, and land cover metrics (Mexia et al., 2018; Swanwick, Dunnett, & Woolley, 2003). To address this, a spatial dataset of parks was created using Ordnance Survey Open Greenspace data which contains several open urban green space types (Ordnance Survey, 2018a). A typology of parks was created using the same methods described in **Chapter 3** to create the brownfield typology, including land cover and landscape analysis of geospatial datasets, and cluster analysis. This produced a park typology dataset for use with i-Tree canopy tool ensuring identical processes were undertaken to assess both typologies. Accuracy assessment was undertaken by training sample verification (200 random points), using Getmapping (2018) aerial imagery and cross-tabulated.

Parks (public parks and gardens in the dataset) were selected as a comparison to brownfield as these are considered some of the largest, abundant and widely distributed vegetated spaces within urban areas (Francis & Chadwick, 2013), providing multiple regulating ecosystem services (Mexia et al., 2018), and are the green space type displaying the greatest area within Greater Manchester in the Ordnance Survey (2018a) data (Fig. 4.1).

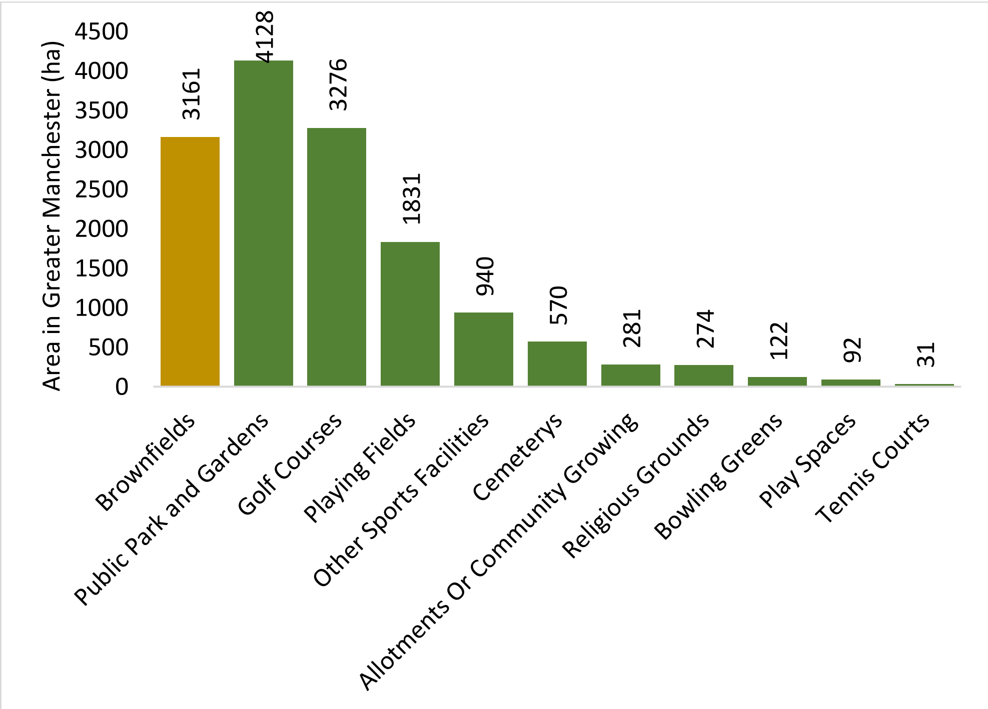


Figure 4.1: The extent of open green space type and brownfield in Greater Manchester. Source: Contains OS data © Crown copyright and database right 2021. (Ordnance Survey, 2021).

The OS Open greenspace technical specifications describe the public parks or gardens data as publicly accessible managed or natural green areas that lie within or close to urban areas (Ordnance Survey, 2018a). Further analysis identifies the urban location of each urban park type based on location of their centroid and percent area within urban, suburban, and peri-urban zones.

4.2.3 City-scale assessment

Each brownfield and urban park type dataset was individually pre-processed, configured and assessed using the i-Tree Canopy tool (Fig. 4.2).

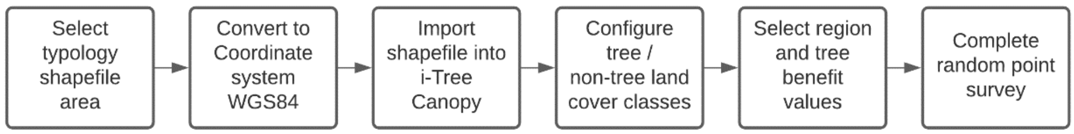


Figure 4.2: Process for i-Tree Canopy analysis.

i-Tree Canopy uses a randomly generated, point based, manual assessment of datasets overlayed on Google Earth aerial imagery to provide estimates of selected land cover classes (Fig. 4.3). Tree canopy cover, and non-tree cover were selected here as only tree canopy cover is utilised for tree benefit analysis (Jacobs, Mikhailovich, & Delaney, 2014), and to limit time expenditure. In total 39,696 individual points were manually assessed as tree/non-tree. Tree canopy cover can be defined as the area of trees, including its leaves, branches, and trunk, obscuring the ground when observed from above, e.g. in an aerial image (Grove, O'Neil-Dunne, Pelletier, Nowak, & Walton, 2006). As each random point is classified the i-Tree Canopy tool provides a running statistical estimate of percentage canopy cover and a standard error. Correspondingly, as more points are classified the standard error decreases, and a more precise estimate of canopy cover is achieved. i-Tree specifications recommend that 500-1000 points are assessed to produce a standard error of approximately ±2% (Doick et al., 2017; i-Tree, 2020a). This can be converted to give a 95% confidence interval, and to allow an acceptable level of accuracy to be achieved. Here random points for each brownfield and park type were generated until a canopy cover standard error of ±1.5 was achieved, which produces a 95% confidence interval that tree canopy estimates deviate less than 3% from the estimated tree canopy cover percentage (Thompson, 2012).

Random point based statistical estimates of cover class (as a percent) are calculated as:

Land cover percentage: $p = n/N$ **_Eq. 4.1_**

Standard error: $\sigma p = \sqrt{}(p(1-p))/N$ **_Eq. 4.2_**

Where N is the number of sample points, n is the number of sample points assigned to a particular class and *p* is the land cover percentage. σ is the population standard deviation (i-Tree, 2011; Mills et al., 2016; Nowak et al., 1996). Percentage tree cover is multiplied by the area analysed to determine the total tree canopy area for each type.

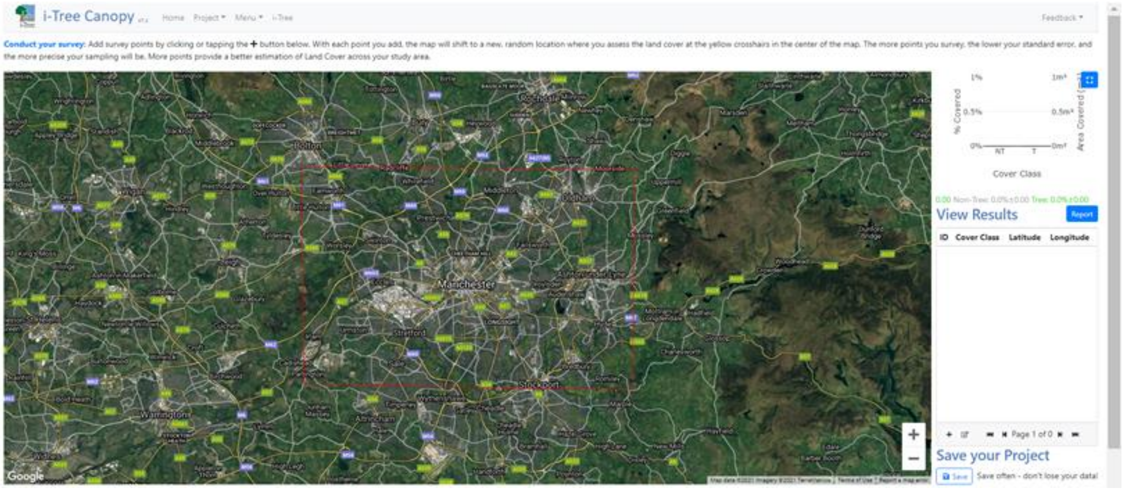


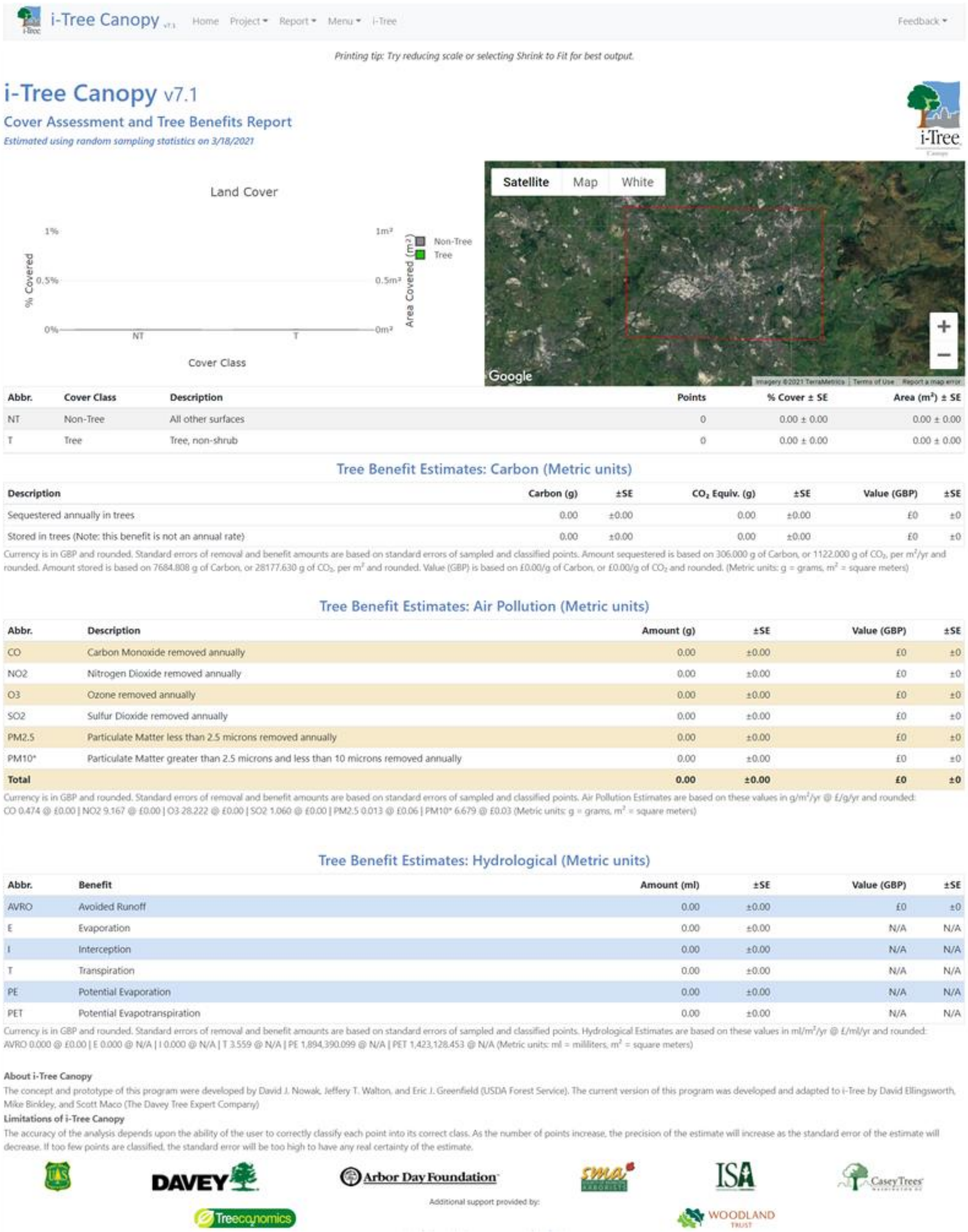
Figure 4.3: The i-Tree Canopy random point survey interface. Image: (i-Tree, 2020b).

Tree canopy area is used to calculate ecosystem services using multipliers to calculate carbon storage and sequestration, removal of several common urban pollutants, and avoided surface water runoff (Table 4.1). These multipliers are derived from parameterised i-Tree Eco data for UK regions, and regional hourly pollution and weather station data relative to the region selected (Henning, 2021). An overview of methods used to generate each multiplier can be found in Nowak (2019), with detailed descriptions in Nowak et al. (2013) for carbon storage and sequestration, air pollution removal in Nowak, Hirabayashi, Bodine, and Greenfield (2014) and Hirabayashi (2016), and hydrological benefits in (Hirabayashi, 2015). This study selected North-West England region (option in the software) for air pollution and carbon sequestration and storage benefit analysis, though due to lack of data availability for hydrological benefits in the North-West region, the England region of the UK was selected for avoided runoff benefits only.

Table 4.1: Tree canopy benefits and multipliers incorporated in i-Tree Canopy.

Abbreviation	**Tree Canopy Benefit Description**	**Removal Rate**
CO	Carbon Monoxide removed annually	4.74 kg/ha/yr)
NO_2	Nitrogen Dioxide removed annually	91.67 (kg/ha/yr)
O_3	Ozone removed annually	282.22 (kg/ha/yr)
PM_{10}	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	66.79 (kg/ha/yr)
$PM_{2.5}$	Particulate Matter less than 2.5 microns removed annually	0.13 (kg/ha/yr)
SO_2	Sulphur Dioxide removed annually	10.60 (kg/ha/yr)
Carbon Sequestered	Carbon Dioxide sequestered annually in trees	3.060 (t/ha/yr)
Carbon stored	Carbon Dioxide stored in trees (Note: this benefit is not an annual rate)	76.848 (t/ha)
Avoided runoff	Avoided surface water runoff by trees	196.774 (m^3/ha/yr)

There is some potential for error when manually classifying tree and non-tree points within i-Tree Canopy. Whilst distinguishing trees and other vegetation from impervious surfaces, built structures, and water etc. in an aerial image is relatively straightforward for an experienced image analyst, discerning between a tree and a tall shrub or other densely vegetated area can be a difficult choice (Kaspar, Kendal, Sore, & Livesley, 2017; Richardson & Moskal, 2014; Rogers & Jaluzot, 2015). To improve the manual classification of points in this instance, contextual information from the surrounding area was taken into consideration by utilising the zoom function in i-Tree Canopy. Additionally, shadows were inspected and used as an indicator to differentiate between trees and other vegetation (Kaspar et al., 2017; Richardson & Moskal, 2014). The outputs of the i-Tree Canopy tool include a report of tree cover percentage, canopy area, and tree benefits including carbon, air pollution, and hydrological conditions (Fig. 4.4).


i-Tree Canopy v7.1 | Home | Project | Report | Menu | i-Tree | Feedback

Printing tip: Try reducing scale or selecting Shrink to Fit for best output.

i-Tree Canopy v7.1

Cover Assessment and Tree Benefits Report

Estimated using random sampling statistics on 3/18/2021

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (m²) ± SE
NT	Non-Tree	All other surfaces	0	0.00 ± 0.00	0.00 ± 0.00
T	Tree	Tree, non-shrub	0	0.00 ± 0.00	0.00 ± 0.00

Tree Benefit Estimates: Carbon (Metric units)

Description	Carbon (g)	±SE	CO_2 Equiv. (g)	±SE	Value (GBP)	±SE
Sequestered annually in trees	0.00	±0.00	0.00	±0.00	£0	±0
Stored in trees (Note: this benefit is not an annual rate)	0.00	±0.00	0.00	±0.00	£0	±0

Currency is in GBP and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 306.000 g of Carbon, or 1122.000 g of CO_2, per m^2/yr and rounded. Amount stored is based on 7684.808 g of Carbon, or 28177.630 g of CO_2, per m^2 and rounded. Value (GBP) is based on £0.00/g of Carbon, or £0.00/g of CO_2 and rounded. (Metric units: g = grams, m^2 = square meters)

Tree Benefit Estimates: Air Pollution (Metric units)

Abbr.	Description	Amount (g)	±SE	Value (GBP)	±SE
CO	Carbon Monoxide removed annually	0.00	±0.00	£0	±0
NO2	Nitrogen Dioxide removed annually	0.00	±0.00	£0	±0
O3	Ozone removed annually	0.00	±0.00	£0	±0
SO2	Sulfur Dioxide removed annually	0.00	±0.00	£0	±0
PM2.5	Particulate Matter less than 2.5 microns removed annually	0.00	±0.00	£0	±0
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	0.00	±0.00	£0	±0
Total		**0.00**	**±0.00**	**£0**	**±0**

Currency is in GBP and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in g/m^2/yr @ £/g/yr and rounded: CO 0.474 @ £0.00 | NO2 9.167 @ £0.00 | O3 28.222 @ £0.00 | SO2 1.060 @ £0.00 | PM2.5 0.013 @ £0.06 | PM10* 6.679 @ £0.03 (Metric units: g = grams, m^2 = square meters)

Tree Benefit Estimates: Hydrological (Metric units)

Abbr.	Benefit	Amount (ml)	±SE	Value (GBP)	±SE
AVRO	Avoided Runoff	0.00	±0.00	£0	±0
E	Evaporation	0.00	±0.00	N/A	N/A
I	Interception	0.00	±0.00	N/A	N/A
T	Transpiration	0.00	±0.00	N/A	N/A
PE	Potential Evaporation	0.00	±0.00	N/A	N/A
PET	Potential Evapotranspiration	0.00	±0.00	N/A	N/A

Currency is in GBP and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in ml/m^2/yr @ £/ml/yr and rounded: AVRO 0.000 @ £0.00 | E 0.000 @ N/A | I 0.000 @ N/A | T 3.559 @ N/A | PE 1,894,390.099 @ N/A | PET 1,423,128.453 @ N/A (Metric units: ml = milliliters, m^2 = square meters)

About i-Tree Canopy

The concept and prototype of this program were developed by David J. Nowak, Jeffery T. Walton, and Eric J. Greenfield (USDA Forest Service). The current version of this program was developed and adapted to i-Tree by David Ellingsworth, Mike Binkley, and Scott Maco (The Davey Tree Expert Company)

Limitations of i-Tree Canopy

The accuracy of the analysis depends upon the ability of the user to correctly classify each point into its correct class. As the number of points increase, the precision of the estimate will increase as the standard error of the estimate will decrease. If too few points are classified, the standard error will be too high to have any real certainty of the estimate.

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Additional support provided by:

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Figure 4.4: The output report generated containing tree canopy cover % and tree benefit estimates. Image (i-Tree, 2020b).

4.2.4 Future potential ecosystem service provision

Based on land cover statistics and area for brownfield and park typologies and using the i-Tree Canopy multipliers, the potential regulating ecosystem service benefits of brownfield and parks was explored through two hypothetical land cover change scenarios. The total ecosystem service provision if all land area for both brownfields and parks was planted with trees (e.g. 100% canopy cover) was calculated. Also, the ecosystem service provision if all pervious land cover was planted with trees was evaluated. This was undertaken for brownfields and parks based on total area within urban, suburban, and peri-urban zones.

4.2.5 Site scale assessment

Ownership significantly influenced case study site selection for the i-Tree Eco field assessment, since unknown or private ownership presents a significant challenge in gaining access to a site for field work, research, or other purposes. Ownership status of brownfield sites in the Greater Manchester area is reported in brownfield register datasets and can be summarised into five ownership categories (Fig. 4.5).

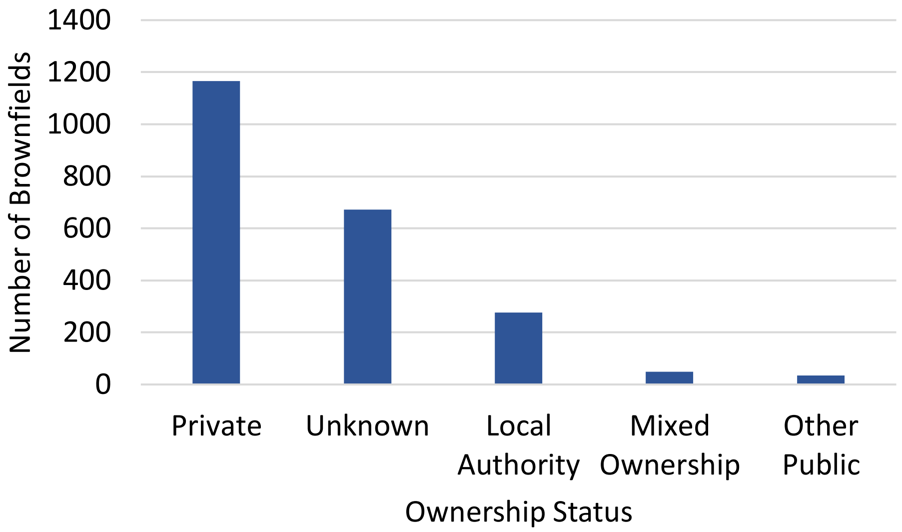

Figure 4.5: Brownfield ownership status in Greater Manchester.

Land ownership details can be bought via the Land Registry Office (HM Land Registry, 2014) for £3 per property search; however, this was impractical due to more than 80% of brownfields being of private or unknown ownership (Fig. 4.5), financial cost, and time constraints due to the large amount of brownfield sites (2197). Several criteria were identified for case study site selection, as follows:

- Permission and access to survey site.
- Brownfield with previous demolition or land disturbance leading to natural vegetation succession, and a park to allow for a comparison of regulating ecosystem service provision, tree structure and composition.
- Multiple trees or shrubs present to enable sufficient field data collection for i-Tree Eco modelling software.
- Abandonment within the last 5-15 years to ensure some spontaneous vegetation had become established.
- Available for redevelopment, to enable assessment of future changes.
- Located within urban and suburban surroundings.

Due to the large private and unknown ownership of brownfield sites within Greater Manchester, several Greater Manchester local authorities, who own multiple brownfield sites and parks, were approached for site access permission. Not all authorities were responsive; however, Bury District Council agreed to grant access permission, and after exploratory site visits, three brownfield sites, and one local park were selected in Radcliffe, Bury (Figs 4.6 – 4.8).

The local township of Radcliffe, in Bury, has a rich industrial past of coal mining, textile and paper making industries (McNeil & Nevell, 2000; Urbed, 2004). It has a population of approximately 35,000 residents (18% of the Bury district) (Office for National Statistics (ONS), 2019), and is 12km from Manchester city centre, and 4.7km from Bury town centre (Urbed, 2004). Industrial activity has declined since the end of the 20th century, leading to socio-economic decay and the loss of several industries, small businesses and infrastructure, leaving a legacy of many brownfield sites in the area (Urbed, 2004). The sites selected are the former Radcliffe High School (RHS) site, former East Lancashire paper mill (ELPM) site, an area of Bradley Fold trading estate (BFTE), and Bolton Road Park (BRP). Sites are located in built-up areas and reflect the industrial heritage and decline of the area, playing an important role locally in the past. Figures 4.7 and 4.8 presents each site's geographical location and position within the local urban environment which are followed by a brief description of each site. Figure 4.8 displays historical images demonstrating site changes over a 19-year period.

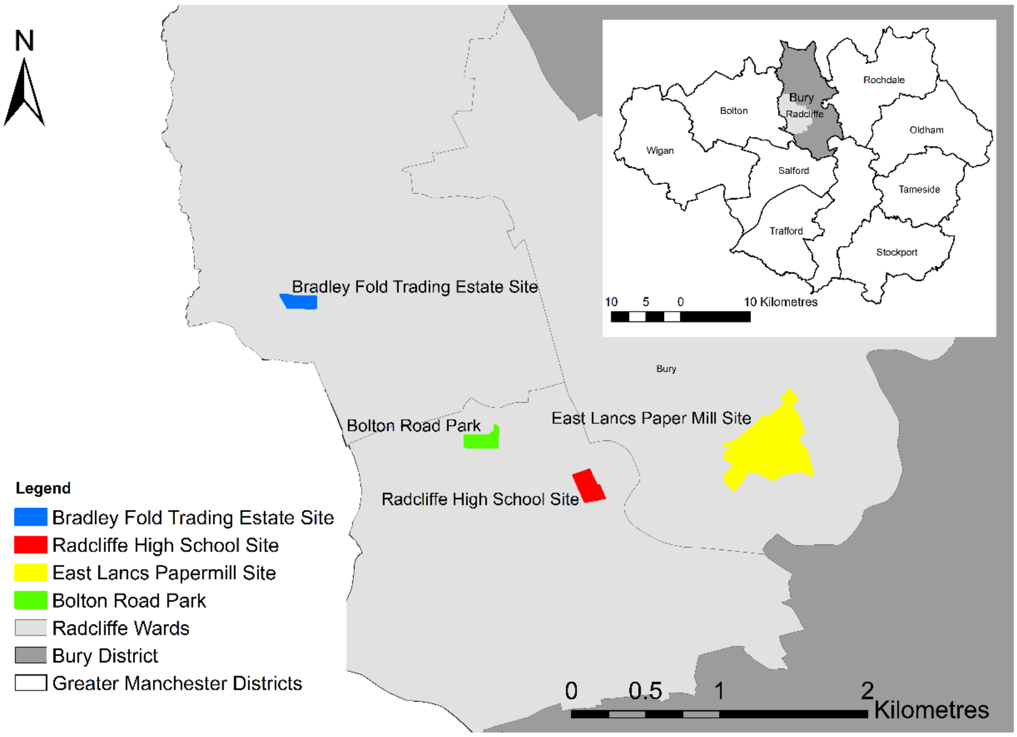

Figure 4.6: The location of the case study sites in Radcliffe, Bury, Greater Manchester. Base maps are © Crown Copyright/database right (2021). An Ordnance Survey/EDINA supplied service. Greater Manchester district boundary data, ONS (2021).

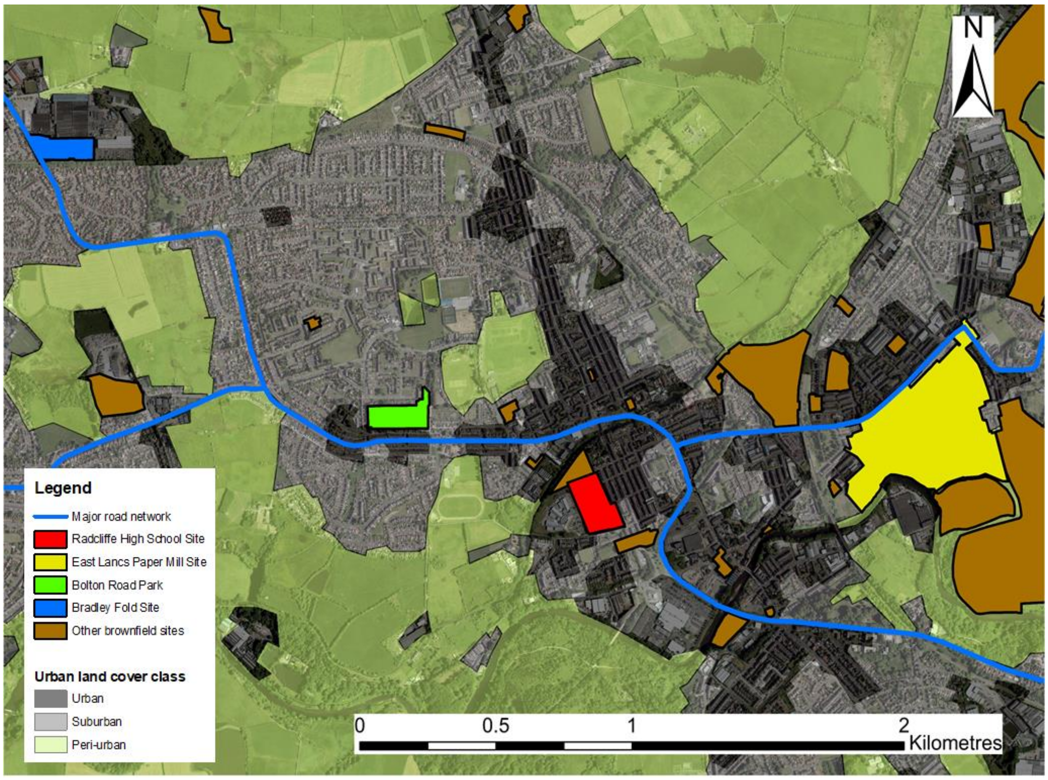

Figure 4.7: Location of the case study sites within the urban environment using a reclassified 2015 land cover map (Rowland et al., 2017), overlayed on aerial imagery of the town of Radcliffe (Getmapping, 2018).

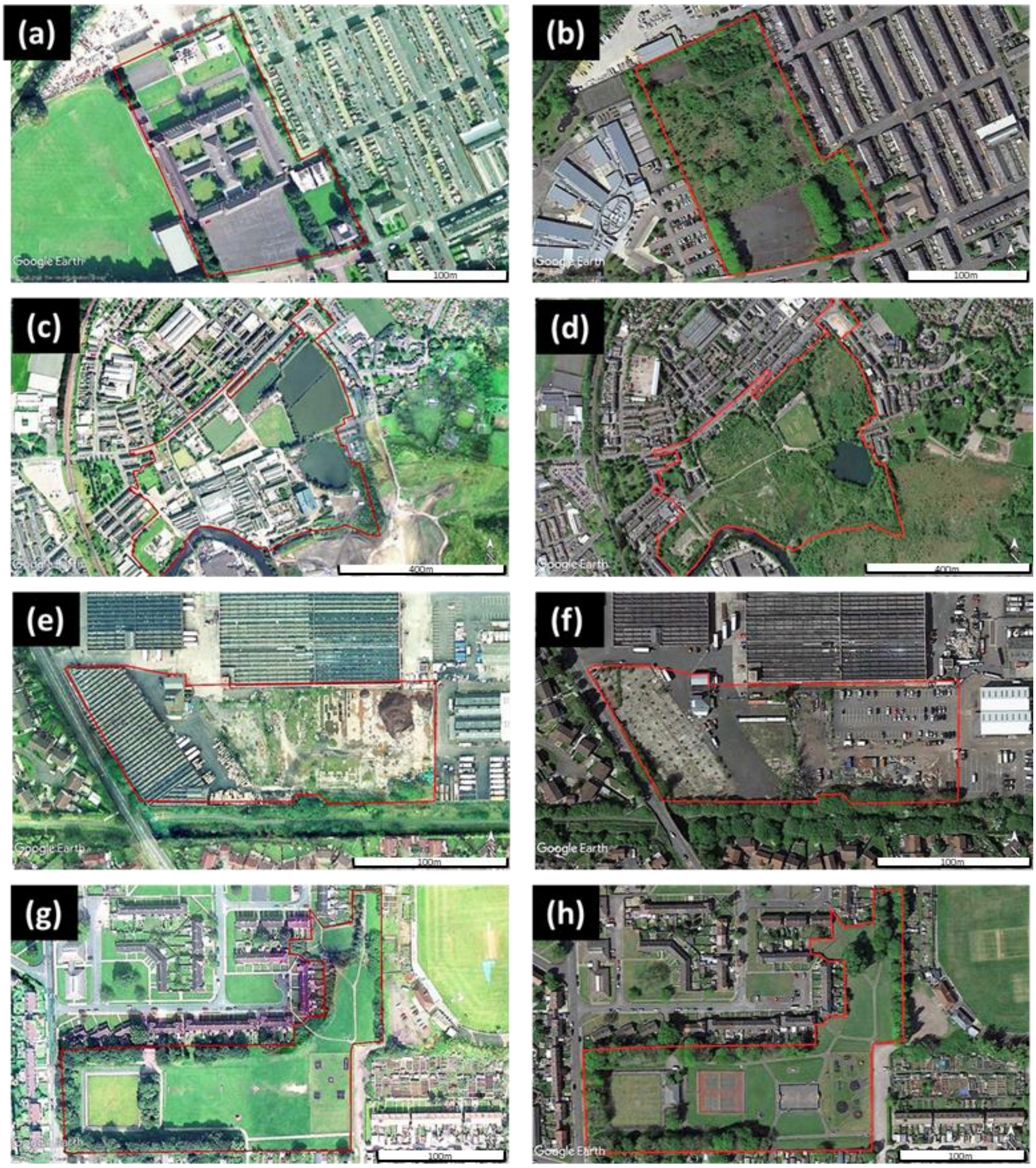

Figure 4.8: Time lapse aerial images of study sites. Radcliffe High School in 2000 (a) and 2019 (b). East Lancs Paper Mill in 2000 (c) and 2019 (d). Bradley Fold Trading Estate in 2000 (e) and 2019 (f). Bolton Road Park in 2000 (g) and 2019 (h). Source: Images (Google Earth, 2020).

Radcliffe High School (RHS)

Previously part of a larger brownfield site used for the construction of the neighbouring Millwood Special School (2011), this site encompasses the site of the former RHS buildings and grounds (Fig. 4.9). It is 2.3 ha in area and located at SD 378067 407129. RHS was founded in 1933 on the site of an early 20th century public park and closed in 2010, being demolished soon after. The site has been vacant and closed to the public for nine years (2010-19), allowing natural vegetation succession to take place without disturbance. The brownfield typology (**Chapter 3**) identifies this site as '(n) Site Remnants and Foundations with Successional

Vegetation', with grass/herbaceous (32%), trees/shrubs (27%), hard surface (26%), and bare earth (<2%) and built structure (<2%). Three main areas of asphalt surface remain on site, including the old playground, and parking areas used by previous staff. The school buildings having been demolished, and vegetation has since colonised the rubble and foundations left behind. The vegetation on site includes mature decorative trees strategically placed around the playground and site perimeter, and dense, self-seeded trees and other vegetation throughout the rest of the site.

Figure 4.9: Radcliffe high school site circa 1990's (a) and circa 2019 (b), both captured from the school gate at the south of the site. Images (a) (Cahill, 2015), (b) (Authors image, 2019).

East Lancashire Paper Mill (ELPM)

The site of the former ELPM is 19.7ha in area and is located at SD 379284 407423. This site has a long industrial heritage, including a former calico printing works (an important process in the textile industry), until the paper mill itself was built in 1860 (Blythe, 2004). Whilst in use, the ELPM was a major employer in the local area (Urbed, 2004) and prospered throughout the 20th century, even containing its own leisure facilities for employees such as tennis courts, bowling greens and more recently a cricket pitch and pavilion (Blythe, 2004). The site closed in 2001 (Blythe, 2004) and ELPM and related structures were demolished in 2005; the site has remained vacant and open ever since (Fig. 4.10) (Bury Council, 2017). The site has developed an early-stage urban forest, with a network of informal tracks and paths. Within the site boundary are the former mill cricket club, which remains in use, and a small area of transport infrastructure to the north. One large ex-industrial mill pond is still present on site to the east. The typology (**Chapter 3**) identified this site as a '(v) Large Open Vegetated', consisting of grass/herbaceous (30%), trees/shrubs (36%), hard surfaces (15%), water (6%), bare earth (6%), and buildings (1%).

Figure 4.10: The main entrance to the East Lancashire Mill circa 1970's (a), and circa 2019 (b). Sources: Image (a) (Howarth, n.d) permission granted, image (b) (Authors image, 2019).

Bradley Fold Trading Estate (BFTE)

BFTE is a 1.7ha section of a working business park owned by Bury Council (Fig. 4.11). The site is located at SD 376104 408426. The site was built pre 1920 and became a Royal Ordnance factory manufacturing munitions before transitioning to engineering (Lancashire at war, n.d.), and later a trading and storage estate. The site has predominately hard surface ground cover which has changed little in the past 15 years. One area of the site, to the east, previously held a warehouse used for RSPCA storage and distribution ('RSPCA plea for old goods,"', 2007). This structure was demolished in 2013, with the concrete slab foundations remaining in place. Vegetation on this site is present along one boundary of the site; however, the building foundations left behind after the warehouse was demolished have some tree and shrub vegetation, colonising the post holes left over from the building's roof support structure. The land cover and typological classification undertaken in **Chapter 3** identified this site as '(c) Impervious grey surface', with land cover including grass (1%), trees, shrubs, and bushes (5%), hard surface (91%), and small areas of bare earth (1%) and built structure (2%).

Figure 4.11: The entrance to Bradley Fold Trading Estate with the RSPCA structure on the right in 2010 and demolished in 2019. Sources: image (a) (Dixon, 2010), image (b) (Authors image, 2019).

Bolton Road Park (BRP)

BRP contains large vegetated areas and several recreational facilities including a bowling green (and pavilion), children's play area, ball zone and tennis courts (Fig. 4.12). The park is located at SD 377320 407485 and is 1.9ha in area. The park is well-maintained and is accessible to the public. Bolton Road Park has held a Green Flag Award since 2005 (Bury Council, 2015). As a national scheme, the Green Flag Award is presented to parks which excel in greenspace management, with criteria such as sustainability, nature conservation, hygiene, upkeep, community connection, heritage, health and safety and general park management (Bury Council, 2015). The park has remained much the same since its establishment in the 1930s, on the site of an early 20th century football pitch. However, some tree and other vegetation removal took place shortly after the millennium to improve public facilities.

Figure 4.12: The entrance (a), and interior of Bolton Road Park. Images: (Authors images, 2019).

The i-Tree Eco assessment utilised a pre-stratified plot-based method (Nowak et al., 2008a). Pre-survey, high resolution aerial images were inspected, and a comprehensive site walk-over was undertaken on each site to identify potential hazards and inaccessible areas, and to ascertain site boundaries, general land cover and vegetation characteristics (Kim et al., 2015; Nowak et al., 2008a). Twenty-five randomly generated field plots of the standard i-Tree Eco size of 0.04ha were generated for each study site using ArcGIS 10.6 (i-Tree, 2019b) (Fig. 4.13). The size and number of plots impact the calculation of standard error, and thus the accuracy of the estimation of the species population and benefits for each area. It has been shown that 200 plots of 0.4ha is sufficient for a 10% standard error for an entire metropolitan area (i-Tree, 2019b; Nowak et al., 2008a; Nowak, Walton, Stevens, Crane, & Hoehn, 2008b). Five random back-up plots were also established in case any original plots were inaccessible. GPS coordinates were established for each plot centre to enable their location in the field (i-Tree, 2019b).

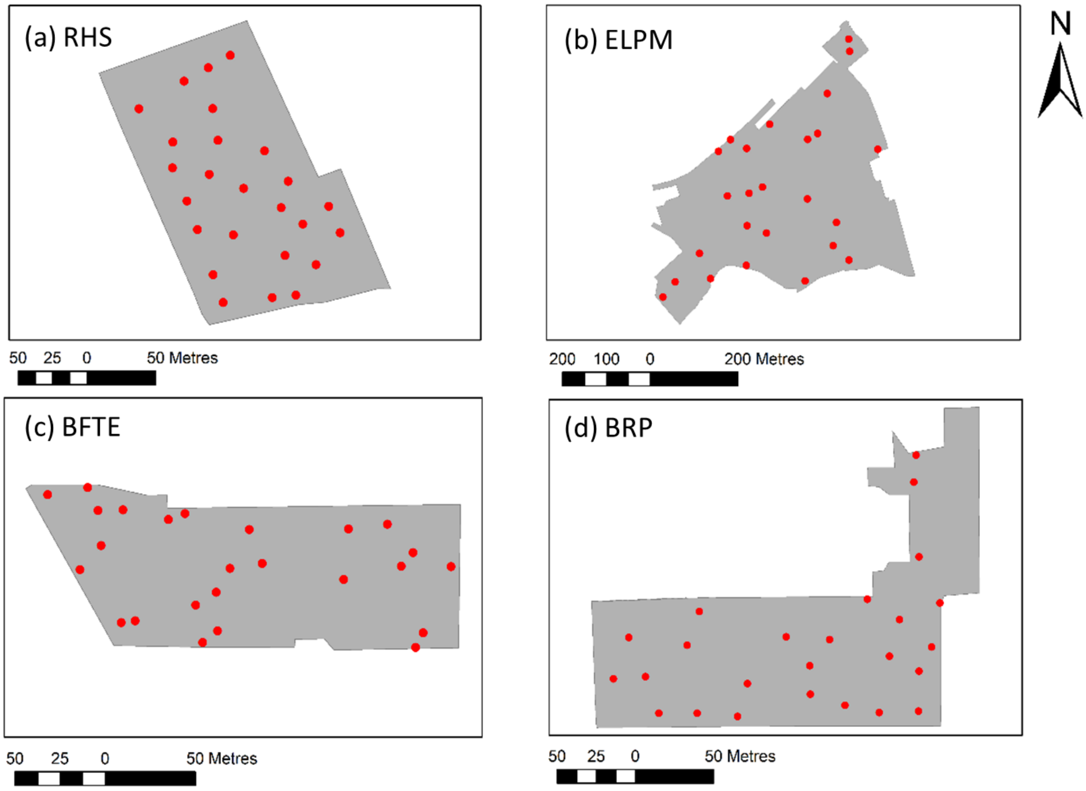

Figure 4.13: Randomly generated plot centres for each site. Fig. 4.13a Radcliffe high school site, Fig.4.13b East Lancashire paper mill site, Fig. 4.13c, Bradley Fold trading estate site, Fig. 4.13d Bolton Road park site.

i-Tree Eco uses field data, together with air pollution and meteorological data to quantify urban forest structure and the regulating ecosystem services provided. At each site, variables were collected in line with the i-Tree plot-based sampling protocol, full details of which are available in technical notes, field manuals and user manuals at www.itreetools.org. All field data were collected during the 2019 leaf-on season (July-August) when more species identification features are evident and acceptable weather conditions are more likely, with remedial site visits in September 2019 for confirmation of some difficult to identify tree species. Several attributes were evaluated for each tree, shrub, and ground cover present in each plot (Table 4.2).

Table 4.2: Data recorded for each plot. Source: Nowak et al. (2008a).

Data recorded	Description
Plot ID	Unique identifier
Plot address	Coordinates of plot centre
Date	Date of plot survey
Photo number	Used to help identify plot
Percent measured	Proportion of the plot that is measured as portions of plot may overlap or cross site boundary
Land use	All recorded as vacant land unless land is still in frequent or intensive use
Tree cover	Percent of plot area covered by tree canopies estimated to nearest 5%
Shrub cover	Percent of plot area covered by shrub canopies estimated to nearest 5%
Shrub species	Species identified using field guides and recorded as such in i-Tree Eco using species list of 10,000 tree and shrub species
Average height of shrub mass	Where mass is a group of shrubs species or genera of similar height (m)
Percent shrub area	Percent of total shrub cover on plot occupied by shrub mass
Percent shrub mass missing	Percent of shrub mass volume (height × ground area) that is not occupied by leaves; estimated to nearest 5%
Tree ID	Unique tree number
Species	Species identified using field guides and recorded as such in i-Tree Eco using species list of 10,000 tree and shrub species
Number of DBH recorded	For multi-stemmed trees
DBH	Diameter at breast height (cm) for all recorded stems
DBH height	Recorded if dbh is not measured at 1.37 m
Total tree height	Height to top of tree (m)
Height to crown base	Height to base of live crown (m)
Crown width	Recorded by two measurements: N-S (north–south) and E-W (east–west) widths (ft/m)
Percent canopy missing	The percent of the crown volume that is not occupied by leaves to the nearest 5%
Dieback	Percent crown dieback to nearest 5%
Percent impervious beneath canopy	Percent of land area beneath entire tree canopy's drip line that is impervious
Percent shrub cover beneath canopy	Percent of land area beneath canopy drip line that is occupied by shrubs
Crown light exposure	Number of sides of the tree receiving sunlight from above; used to estimate competition and growth rates

Trees and shrubs were distinguished following the i-Tree (2019) definition whereby trees have DBH greater than or equal to 2.54 cm, and shrubs less than 2.54 cm. Woody vegetation less than 30.5 cm in height was recorded as herbaceous cover (i-Tree, 2019a; Nowak et al., 2008a). Species identification was undertaken using multiple tree and vegetation identification resources (Johnson & More, 2006; Poland & Clement, 2009; Stace, 2010). Species were identified using several features, including leaf characteristics, bark, size, buds, fruits, and seeds. All species were identified at genus level as a minimum (Poland & Clement, 2009). Unidentified species were recorded and photographed for later identification. Once field data collection was complete, data was input into the i-Tree Eco program and regional weather and pollution monitoring stations were selected based on the most complete data at the time of analysis. The same data monitors were also selected for the largest i-Tree Eco survey undertaken to date by City of Trees (City of Trees Manchester, 2018b). Shawbury weather station in North-West England was selected as the most complete dataset and similar elevation to Greater Manchester. This data recorded the total annual precipitation as 317 millimetres (2013). Air pollution data (2015) for O_3 NO_2 SO_2 $PM_{2.5}$ was collected from North-West England monitoring stations (Manchester Piccadilly, Manchester Airport), however, data for CO was sourced from Yorkshire and Humber (Leeds) station, as no complete data for the North-west was available.

4.3 Results

4.3.1 Park typology

A typology of parks within Greater Manchester was created to enable comparison with brownfield. The Ordnance Survey open green space data contained 380 parks in Greater Manchester with a total area of 4128 hectares. In comparison, brownfields comprise 2197 sites and 3161 hectares. The park typology analysis identified twelve types of park which vary in terms of land cover and landscape metrics (Fig. 4.14). **Appendix 4.1** briefly describes each type of park based on data and aerial interpretation of parks within each type. This is accompanied in **Appendix 4.1** by aerial imagery which provides examples of the twelve types of park identified in Greater Manchester.

Figure 4.14 presents the results for the supervised land cover classification for the park typology, alongside urban distribution by area and site centroid. It is clear that most park types are highly pervious and vegetated. This analysis identified under construction or modification as the most pervious type, grassland parks as the most vegetated, and small wooded parks contain highest tree/shrub cover. Hard play parks display the most impervious land cover. It is apparent that most parks are centrally located in suburban and peri-urban areas (Figure 4.14). Those with greater impervious land cover occur most frequently in urban areas. A confusion matrix reporting accuracy by land cover class is presented in Table 4.3, overall accuracy was 91% (Kappa 0.87).

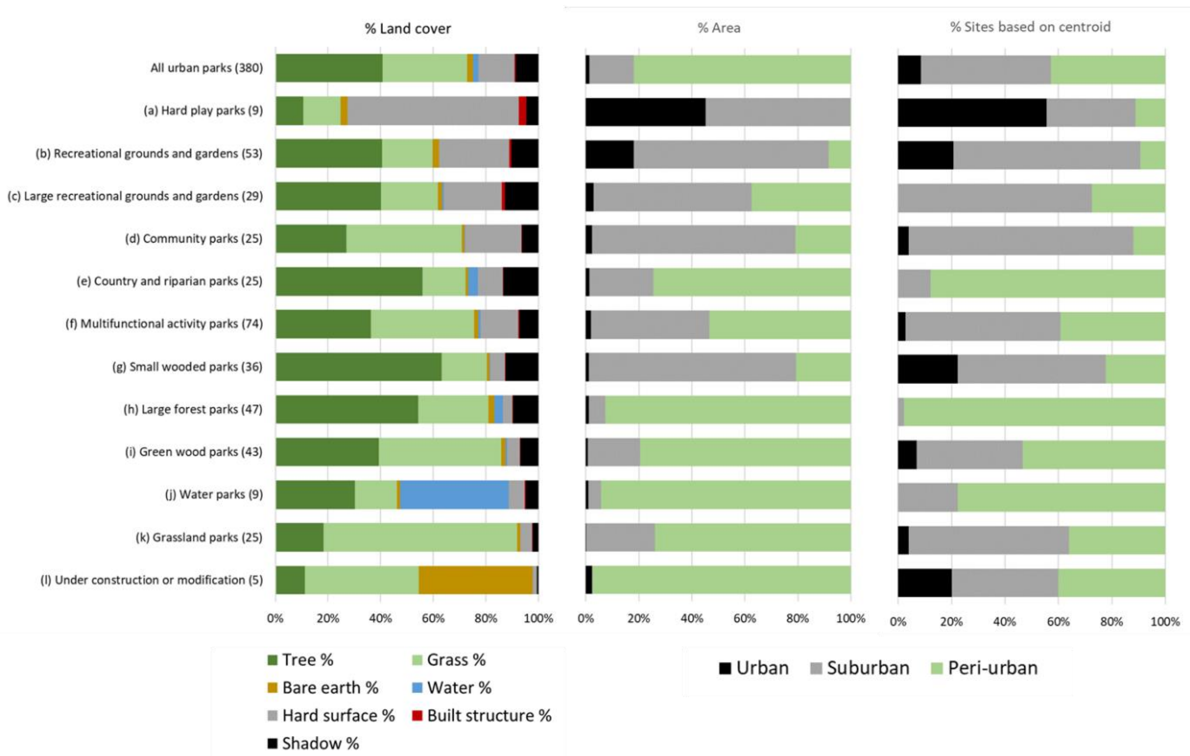

Figure 4.14: Land cover percentages for each urban park type and the distribution of parks by % area and percent number (based on site centroid) within Greater Manchester. Types organised by total perviousness, number of parks in parentheses. (Note (k) grassland parks has one very small park (0.16 ha) with centroid in an urban zone and area is negligable as a percentage of area).

Table 4.3: A confusion matrix presenting accurracy of brownfield land cover classification.

Class	Trees and shrubs	Grass/herbaceous	Bare earth	Water	Hard surface	Built structure	Shadow	**Total**	**User Accuracy**	**Kappa**
Trees and shrubs	76	10	0	1	0	0	1	88	0.86	0
Grass/herbaceous	0	59	0	0	0	0	1	60	0.98	0
Bare earth	1	1	8	0	0	0	0	10	0.80	0
Water	1	1	0	13	0	0	0	15	0.87	0
Hard surface	1	1	0	0	11	0	0	13	0.85	0
Built structure	0	0	0	0	0	10	0	10	1.00	0
Shadow	0	0	0	0	0	0	18	18	1.00	0
Total	79	72	8	14	11	10	20	214	0.00	0
Producer Accuracy	0.96	0.82	1.00	0.93	1.00	1.00	0.90	0.00	0.91	0
Kappa	0	0	0	0	0	0	0	0	0	0.88

Landscape metrics for the urban park typology reveal that those with the largest mean size are water parks and large forest parks, whilst the smallest are hard play parks and small wooded parks (Table 4.4). Community parks and those under construction/modification have the most level topography. Whilst large forest parks and country and riparian parks have the most uneven topography. In terms of shape, the area weighted mean shape index identifies hard play parks and recreation grounds and gardens as the most regular in shape, and large forest parks, country and riparian parks, and water parks are irregularly shaped.

Table 4.4: Landscape metrics statistics for the urban park typology.

Park typology	Nº of sites	Area (ha)			Slope (degrees)		Perimeter area ratio		Area weighted mean shape index		Mean patch fractal dimension	
	n	Sum	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
(a) Hard play parks	9	2.2	0.2	0.3	2.2	1.9	0.1	0.1	1.2	0.1	1.4	0.1
(b) Recreational grounds and gardens	53	35.8	0.7	0.6	2.3	2.0	0.1	0.0	1.3	0.2	1.4	0.1
(c) Large recreational grounds and gardens	29	125.0	4.3	2.4	3.0	2.5	0.0	0.0	1.4	0.3	1.3	0.0
(d) Community parks	25	46.7	1.9	1.6	1.3	0.9	0.1	0.0	1.3	0.3	1.3	0.1
(e) Country and riparian parks	25	218.9	8.8	4.9	5.8	4.5	0.0	0.0	2.2	1.3	1.4	0.1
(f) Multifunctional activity parks	74	472.8	6.4	6.7	2.1	1.3	0.0	0.0	1.4	0.3	1.3	0.0
(g) Small wooded parks	36	18.2	0.5	0.6	2.6	3.1	0.1	0.1	1.6	0.6	1.4	0.1
(h) Large forest parks	47	1902.7	40.5	45.1	6.0	3.2	0.0	0.0	2.8	1.2	1.4	0.1
(i) Green wood parks	43	499.0	11.6	14.5	2.3	1.9	0.0	0.0	1.7	0.6	1.3	0.1
(j) Water parks	9	685.6	76.2	111.1	3.2	1.5	0.0	0.0	2.0	0.6	1.3	0.0
(k) Grassland parks	25	88.9	3.6	5.3	2.6	3.0	0.1	0.1	1.4	0.3	1.4	0.1
(l) Under construction or modification	5	32.2	6.4	11.3	1.9	1.3	0.1	0.1	1.4	0.4	1.4	0.1
All urban parks	**380**	**4128.0**	**10.9**	**28.3**	**3.0**	**2.8**	**0.1**	**0.1**	**1.7**	**0.8**	**1.3**	**0.1**

4.3.2 Ecosystem service provision of brownfield and park typologies

Table 4.5 provides the estimated regulating ecosystem services for all brownfields and parks across Greater Manchester. This shows that parks provide almost three times the amount of regulating ecosystem service benefits that brownfields do (Table 4.5). It is observed that parks store an estimated 143,000 tonnes of carbon to brownfields 52,000 tonnes, whilst parks sequester a further 5,696 tonnes per year, and brownfields 2,066 tonnes. The same pattern is observed for both estimated annual air pollution removal (840t to 305t) and annual avoided runoff (366,000m^3 to 133,000m^3) by trees at parks and brownfield. The pollutants removed in the greatest quantities are O_3 and NO_2, while dry deposition of particulate matter is significantly greater for PM_{10} than $PM_{2.5}$.

Table 4.5: Greater Manchester estimated regulating ecosystem services for all brownfields and parks.

Ecosystem benefit	All brownfields		All parks	
	Total	mean/ha	Total	mean/ha
Carbon stored (t)	51,888	16.42	143,046	34.65
Carbon sequestered annually (t)	2,066	0.65	5,696	1.38
Total pollution removed annually (kg)	304,793	96.42	840,255	203.55
Carbon Monoxide removed annually (kg)	3,201	1.01	8,829	2.14
Nitrogen Dioxide removed annually (kg)	61,896	19.58	170,634	41.34
Ozone removed annually (kg)	190,560	60.28	525,339	127.26
Sulphur Dioxide removed annually (kg)	7,155	2.26	19,724	4.78
Particulate Matter greater than 2.5 microns and less than 10 microns removed annually (kg)	45,094	14.27	124,316	30.12
Particulate Matter less than 2.5 microns removed annually (kg)	88	0.03	242	0.06
Total avoided runoff annually (kl)	132,864	42.03	366,280	88.73

A comparison of total regulating ecosystem service provision by trees on brownfield and park typologies is presented in Figure 4.15. This demonstrates that large forest parks significantly out-perform all other parks and brownfield types in terms of regulating ecosystem service provision, which can be attributed to their significant area and high proportion of canopy cover. Water parks also provide more benefits than any type of brownfield in Greater Manchester. Brownfield types with the greatest ecosystem service benefits include very large open green space and large open vegetated. Several impervious or infrequently occurring brownfield types provide negligible ecosystem services in comparison to the urban park typology at the city scale. The lowest level of ecosystem service provision was observed in hard play parks (urban parks), which are also highly impervious and fewer in number.

In terms of mean ecosystem service provision by unit area (ha) for each type, brownfields are more comparable to urban parks. Three types of park provide more regulating ecosystem services per hectare than any brownfield type (Fig. 4.16). These include small woodland parks, country and riparian parks, and large forest parks. However, four brownfield types out-perform all other park types including irregularly shaped and vegetated, vegetated with water body, uneven and vegetated, and densely vegetated.

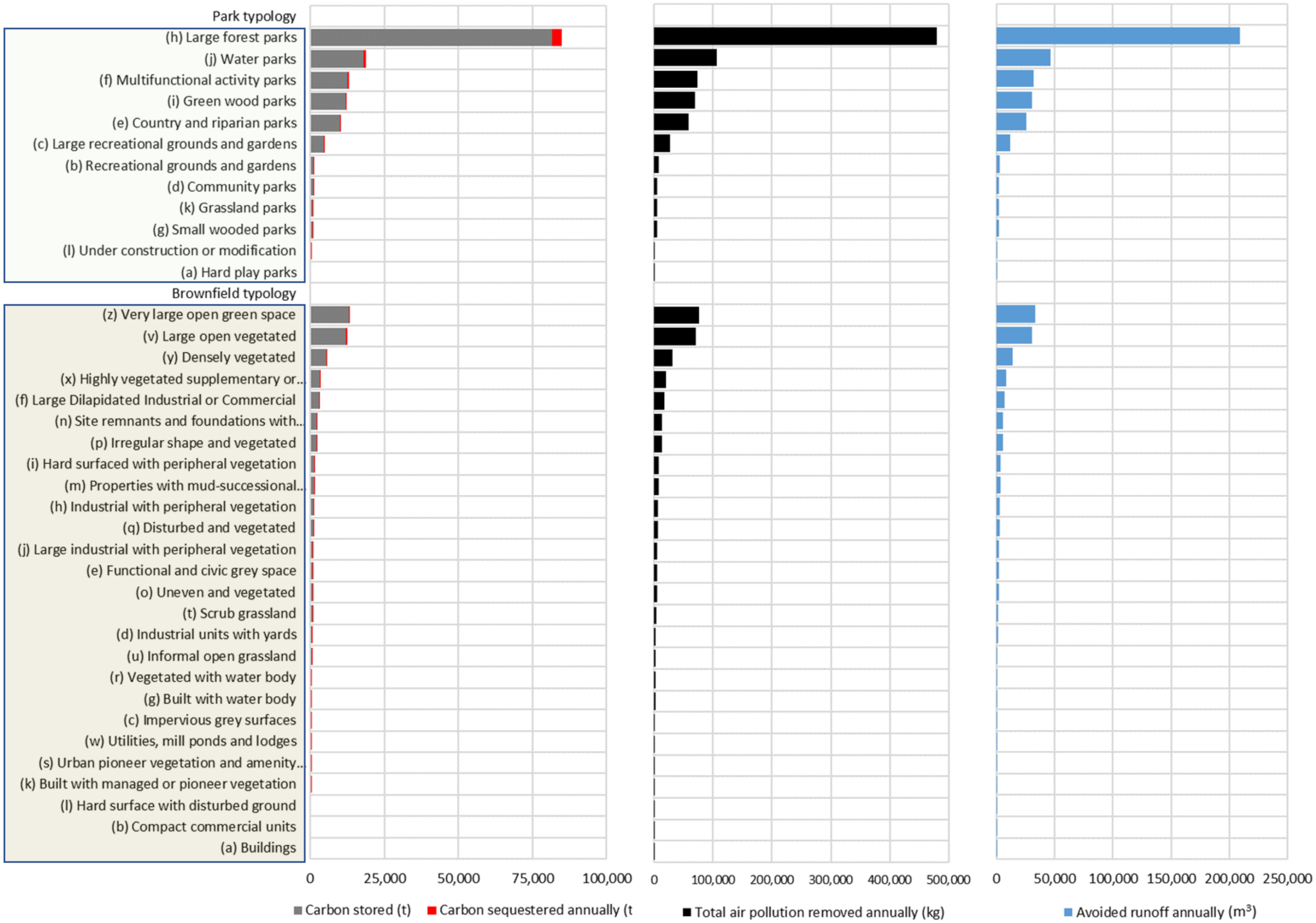

Figure 4.15: Total regulating ecosystem services provision by typology in Greater Manchester.

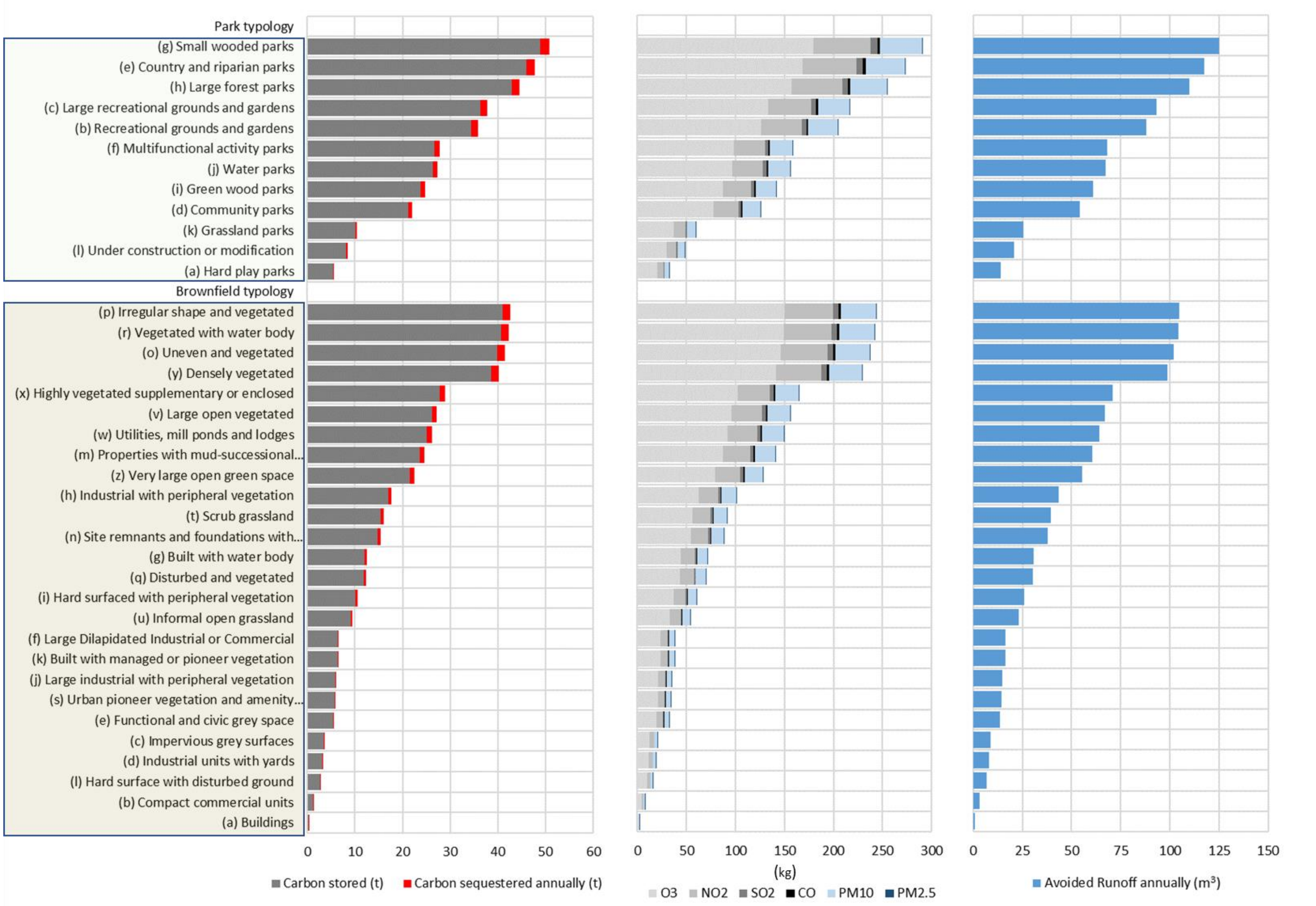

Figure 4.16: The mean regulating ecosystem services provision per hectare by typology.

4.3.3 The urban distribution of brownfield and park ecosystem service provision

Focusing on how brownfields and parks, and their associated regulating ecosystem services, are spatially distributed within urban, suburban and peri-urban areas in Greater Manchester reveals some significant findings. Based upon area within each urban zone, there is a distinct contrast in the distribution of parks and brownfields (Figure 4.17). Brownfield area exceeds park area in urban areas, is comparable in suburban areas, and significantly lower than parks in peri-urban areas.

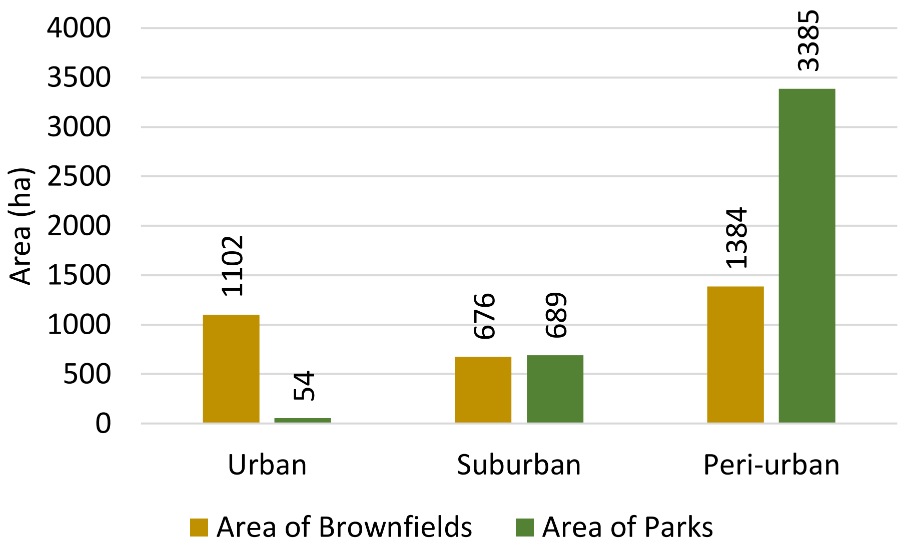

Figure 4.17: The uneven distribution of parks and brownfields in urban, suburban and peri-urban areas in Greater Manchester.

Further analysis of urban ecosystem service provision, based on the area of brownfield and park types, within urban, suburban and peri-urban areas in Greater Manchester, is presented in Table 4.6. Due to the greater area of brownfields within urban areas compared to parks, brownfields make a particularly important contribution to ecosystem service provision within urban areas, delivering approximately five times the ecosystem services (Table 4.6). Whilst the extent of parks and brownfields is similar in suburban areas, brownfields are revealed to provide almost half the amount of ecosystem service benefits that are provied by parks. Parks are also the dominant providers of ecosystem services in peri-urban areas.

Table 4.6: The total regulating ecosystem service provision by parks and brownfields in urban, suburban and peri-urban areas of Greater Manchester.

Urban zone benefits	Urban		Suburban		Peri-urban	
	Parks	Brownfields	Parks	Brownfields	Parks	Brownfields
Urban area (ha)	54	1,102	689	681	3,385	1,411
Carbon stored (t)	1,847	9,586	21,656	11,126	119,543	32,053
Carbon sequestered annually (t)	74	382	862	443	4,760	1,276
Carbon Monoxide removed annually (kg)	114	558	1,336	686	7,378	1,979
Nitrogen Dioxide removed annually (kg)	2,204	11,400	25,832	13,270	142,598	38,234
Ozone removed annually	6,785	35,099	79,532	40,856	439,021	117,713
Sulphur Dioxide removed annually (kg)	255	1,318	2,986	1,534	16,483	4420
Particulate Matter greater than 2.5 microns and less than 10 microns removed annually (kg)	1,606	8,306	18,820	9,668	103,890	27,856
Particulate Matter less than 2.5 microns removed annually (kg)	3	16	37	19	202	54
Avoided Runoff annually (m^3)	4,731	24,459	55,452	28,486	306,097	82,073

Figure 4.18 provides a visualisation for regulating ecosystem services provided by park and brownfield typologies within urban, suburban and peri-urban areas in Greater Manchester. Further details of individual air pollutant removal for each type in each urban zone are presented in **Appendix 4.2**. This was calculated as the product of the mean ecosystem service provision by each type and the area of each type within the urban, suburban and peri-urban zones. The analysis illustrates the significantly greater ecosystem benefits provided by brownfield tree canopy in urban areas when compared to parks. Although area is limited, large forest parks provide the greatest ecosytem services of all parks in urban zones. However, this is surpassed by large dilapidated industrial and commercial and large open vegetated brownfields. Several other brownfield types provide more carbon storage and sequestration, air pollution removal, and avoided runoff than all other park types in urban areas (Fig. 4.18). In suburban areas, large forest parks and multifunctional activity parks provide the most regulating ecosystem services, though densely vegetated and highly vegetated supplementary or enclosed brownfields provide more than all but the most five productive park types (Fig. 4.18). In peri-urban areas regulating ecosystem services by parks dominate brownfield, in particular large forest parks. The most productive brownfields in peri-urban areas are large open vegetated, very large open green space, and densely vegetated (Fig. 4.18).

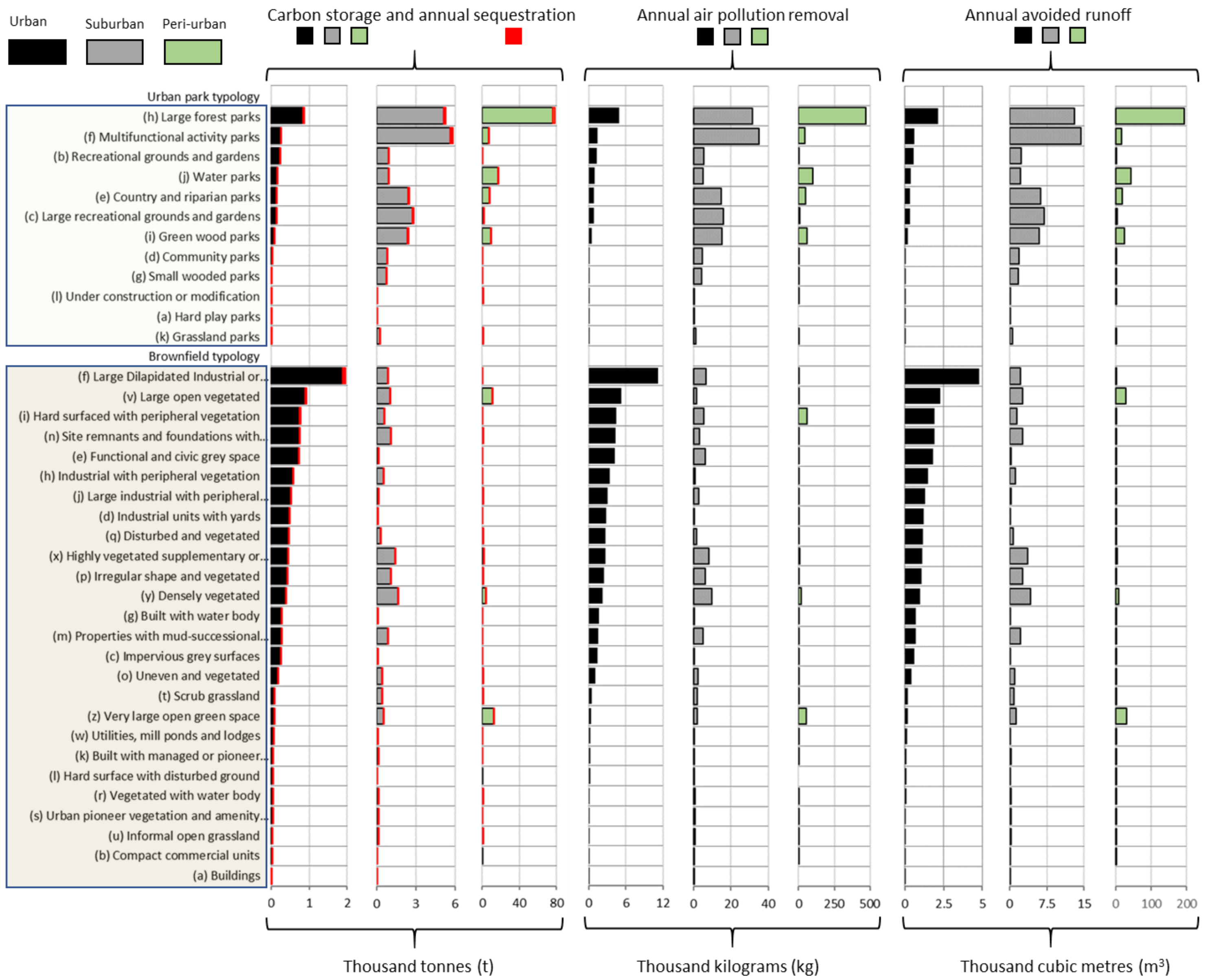

Figure 4.18: The total regulating ecosystem service provision of parks and brownfield within each urban zone in Greater Manchester.

4.3.4 Tree planting scenarios

To gain an understanding of the maximum potential regulating ES provision by brownfields and parks, two hypothetical scenarios were considered: (i) tree planting to achieve 100 percent canopy cover and (ii) planting trees only on the existing plantable area (grass/herbaceous plants and bare earth land cover classes). Brownfields in densely built urban areas have the potential to increase ecosystem service provision approximately nine times more than parks (e.g. brownfields 64,391kg to parks 7,376kg estimated potential annual air pollution removal) when only existing plantable space is forested (Table 4.7). This disproportion between brownfield and parks ecosystem service provision increases significantly if all man-made structure and surfaces on brownfield are cleared and forested in urban areas. If 100 percent canopy was installed on all brownfield and parks in urban areas, brownfield would provide >20 times the ecosystem services of parks (e.g. annual air pollution removal, brownfields 502.7t, parks 24.6t). This is an increase of 797% for brownfields, and 125% for parks.

Table 4.7: The potential ecosystem service provision of brownfields and parks in urban areas under two hypothetical land cover change scenarios.

Land cover change scenario												
(i) 100 percent tree canopy cover	**Brownfield area (ha)**	Potential carbon stored (t)	Potential carbon seq. annually (t)	Potential air pollution removed annually (kg)	Total avoided runoff annually (m^3)	**% Increase**	**Park area (ha)**	Potential carbon stored (t)	Potential carbon seq. annually (t)	Potential air pollution removed annually (kg)	Potential avoided runoff annually (m^3)	**% Increase**
Total within urban area	1,102	84,686	3,372	502,677	216,841	**797**	54	4,150	165	24,632	10,626	**125**
Total within suburban area	676	51,949	2,069	308,357	133,017	**367**	689	52,948	2,108	314,287	135,575	**144**
Total within peri-urban area	1,384	106,358	4,235	631,312	272,330	**232**	3,385	260,130	10,358	1,544,068	666,066	**118**
~~**Potential space for tree planting**~~												
(ii) All plantable space planted with trees	**Brownfield plantable area (ha)**	Potential carbon stored (t)	Potential carbon seq. annually (t)	Potential air pollution removed annually (kg)	Total avoided runoff annually (m^3)	**% Increase**	**Park plantable area (ha)**	Potential carbon stored (t)	Potential carbon seq. annually (t)	Potential air pollution removed annually (kg)	Potential avoided runoff annually (m^3)	**% Increase**
Plantable space in Urban areas	141	10,848	432	64,391	27,776	**114**	16	1,243	49	7,376	3,182	**67**
Plantable space in Suburban areas	165	12,681	505	75,270	32,469	**114**	242	18,587	740	110,327	47,592	**86**
Plantable space in Peri-urban areas	619	47,557	1,894	282,284	121,769	**148**	1,038	79,786	3,177	473,591	204,293	**67**

4.3.5 Case study site findings

Results from site scale investigation of brownfield and park tree structure, reveal that brownfields have very different tree structure and composition to that of parks (Table. 4.8 & 4.9). The i-Tree Eco extrapolation of tree population revealed ELPM to contain the highest tree count, and the greatest tree and shrub cover, and the lowest at BRP (Table 4.8). The results revealed RHS to contain the highest tree density, with the lowest at BRP (Table 4.8). Overall, the area weighted mean tree density of the brownfield study sites was 363 trees per hectare.

Table 4.8: Case study sites type, tree population, tree density and tree canopy and shrub cover for all study sites.

Case study site	Brownfield/park type	Projected number of trees	Tree density per hectare	Tree canopy %	Shrub cover %
East Lancs Paper Mill (ELPM)	(v) Large open vegetated space	7304	370	35.6	16.3
Bradley Fold Trading Estate (BFTE)	(c) Impervious grey surface	58	34	2.5	4.4
Radcliffe High School (RHS)	(n) Site remnants and foundations with successional vegetation	1259	547	35	8.5
Bolton Rd Park (BRP)	(d) Community parks	47	25	15.6	0.4

Table 4.9 provides the tree species composition at each study site. The three most common species found across all brownfields are Silver birch (*Betula pendula*) (43.9%), Osier willow (*Salix viminalis*) (25.6%) and Goat willow (*Salix caprea*) (16.1%) (Table 4.9). BRP's most dominant species being Common ash (*Fraxinus excelsior*) (31.9%), and Wild cherry (*Prunus avium*) (25.5%) (Table 4.9). *Betula pendula* is the dominant species on all three brownfield study sites, though absent from BRP. *Salix caprea* is also present at all brownfields (Table 4.9). Table 4.9 shows that the diversity and evenness of species at BRP are marginally higher than brownfield sites ELPM and BFTE, and RHS displays a lower diversity and evenness. This emphasises that whilst RHS displays the greatest species richness, and density, it is primarily dominated by one species (*Betula pendula*). BRP has a lower number of species present, but the individuals in the community are distributed more equally among these species (Table 4.9). Park tree composition and structure is notably different to the three brownfield study sites. This is also emphasised in original urban forestry research in Greater Manchester by City of Trees (City of Trees Manchester, 2018a). Analysis of their data reveals significantly different tree species composition on parks and other land uses within Greater Manchester than the brownfields examined here (**Appendix 4.3**).

Table 4.9: Tree species population statistics, tree species richness, density, diversity, and evenness for each study site.

Parameter	East Lancs Paper Mill	Radcliffe High School	Bradley Fold Trading Estate	Bolton Rd Park
Tree species population				
Silver birch *(Betula pendula)*	37.0%	84.0%	43.1%	
Osier willow *(Salix viminalis)*	30.1%	0.2%		
Goat willow *(Salix caprea)*	18.1%	4.9%	10.3%	
Willow spp. *(Salix)*	5.2%			
Bay willow *(Salix pentandra)*	3.3%			
White poplar *(Populus alba)*	2.5%	0.4%		14.9%
Butterfly-bush *(Buddleja davidii)*	1.6%		32.8%	
Sycamore *(Acer pseudoplatanus)*	0.5%	1.0%		10.6%
Hawthorn *(Crataegus monogyna)*	0.5%		3.4%	4.3%
Norway maple *(Acer platanoides)*	0.3%	4.2%		
Hornbeam *(Carpinus betulus)*	0.3%			
Common ash *(Fraxinus excelsior)*	0.3%	1.3%		31.9%
Crab apple *(Malus sylvestris)*	0.3%			
Large-leaved lime *(Tilia platyphyllos)*		1.7%		
Broom *(Cytisus scoparius)*		1.3%		
Plum spp. *(Prunus)*		0.4%		
Horse chestnut *(Aesculus hippocastanum)*		0.2%		
Apple spp. *(Malus)*		0.2%		
Wild cherry *(Prunus avium)*		0.2%	3.4%	25.5%
Grey willow *(Salix cinerea)*		0.2%		
Dog rose *(Rosa canina)*			3.4%	
Whitebeam *(Sorbus aria)*			3.4%	
Wilson holly *(Ilex x altaclarensis)*				4.3%
English elm *(Ulmus procera)*				4.3%
Species Richness	13	14	7	7
Species per hectare (spp/ha)	12.8	13.8	6.9	6.9
Shannon-Wiener diversity index	1.6	0.7	1.4	1.7
Shannon-Wiener evenness index	0.6	0.3	0.7	0.9

Table 4.10 presents the regulating ecosystem service provision by trees at each study site and per hectare. The ELPM site provides the highest total ecosystem benefits, with BFTE providing significantly less benefits than all other study sites (Table 4.10). Interestingly, examination of ecosystem service provision per hectare reveals RHS to provide more carbon storage and sequestration, and avoided runoff per hectare than other sites, though ELPM removes marginally more air pollutants annually due to different tree species composition. BFTE is shown to provide the least ecosystem benefits.

Table 4.10: A summary of total ecosystem service provision for each study site and per hectare.

Parameter measured	East Lancs Paper Mill (ELPM)	Radcliffe High School (RHS)	Bradley Fold Trading Estate (BFTE)	Bolton Rd Park (BRP)
Area (ha)	19.7	2.3	1.9	1.9
Number of Trees	7,304.0	1,259.0	58.0	47.0
Carbon Storage (t)	1,174.4	449.7	8.1	251.4
Gross Carbon Sequestration (t)	57.3	11.9	0.5	1.9
Avoided Runoff (m^3/yr)	383.1	79.9	4.2	29.8
Pollution Removal (kg/yr)	356.3	40.8	4.9	14.1
Tree benefits per hectare				
Carbon Storage (t/ha)	59.6	195.5	4.3	132.3
Gross Carbon Sequestration (t/ha/yr)	2.9	5.2	0.3	1.0
Avoided Runoff (m^3/ha/yr)	19.4	34.7	2.2	15.7
Pollution Removal (kg/ha/yr)	18.1	17.7	2.6	7.4

Individual air pollutant removal for each site, on an absolute, per unit area, and mean tree removal basis, are presented in Table 4.11. O_3 is the air pollutant exhibiting the greatest annual removal rate, followed by NO_2. ELPM is found to remove the greatest amount of air pollutants and BFTE the least.

Table 4.11: Individual air pollutants removed annually for each study site.

	Annual pollutant removal (kg)				
Study site	**CO**	**NO_2**	**O_3**	**$PM_{2.5}$**	**SO_2**
East Lancs Paper Mill (ELPM)	4.8	86.6	239.8	13.4	11.7
Radcliffe High School (RHS)	0.5	10	27.2	1.8	1.3
Bradley Fold Trading Estate (BFTE)	0.1	1.2	3.3	0.2	0.2
Bolton Rd Park (BRP)	0.1	2.9	8	0.5	0.4
	Annual pollutant removal by unit area (kg/ha)				
Study site	**CO**	**NO_2**	**O_3**	**$PM_{2.5}$**	**SO_2**
East Lancs Paper Mill (ELPM)	0.24	4.39	12.16	0.68	0.59
Radcliffe High School (RHS)	0.2	4.34	11.82	0.8	0.56
Bradley Fold Trading Estate (BFTE)	0.03	0.71	1.92	0.14	0.09
Bolton Rd Park (BRP)	0.09	1.81	4.95	0.33	0.24
Mean tree air pollution removal from:	**Pollution Removed (g/yr)**				
Study site	**CO**	**NO_2**	**O_3**	**$PM_{2.5}$**	**SO_2**
East Lancs Paper Mill (ELPM)	0.44	20.98	7.51	1.04	1.06
Radcliffe High School (RHS)	0.3	17.4	6.39	0.83	1.17
Bradley Fold Trading Estate (BFTE)	0.36	20.24	7.42	0.96	1.35
Bolton Rd Park (BRP)	3.46	193.08	70.22	9.31	12.07

Analysis of the mean ecosystem benefits for individual tree species, and the mean tree ecosystem services at each site is presented in Table 4.12. The difference in the range of measured tree DBH is presented in Figure 4.19, where relatively few mature trees are identified at brownfield sites, and only mature trees are measured at BRP. Results reveal that the pollution removed by an average tree on BRP was significantly greater than that for the brownfield types. Unsurprisingly, larger more mature trees (high DBH) provide more regulating ecosystem services per tree (e.g. *Ulmus procera*), though it should be noted that tree species reaching full maturity, carbon storage will level out and annual sequestration rates will reduce (Nowak & Crane, 2002), which is visible in Figure 4.20 for BRP annual sequestration. Maximum DBH can depend on species, health and external factors such as management or damage. This is evident at BRP where mean tree DBH is 120.6cm (Fig. 4.19) and ecosystem services for typical trees are significantly greater (Table 4.12). Trees on brownfield sites are commonly less mature, thus provide less regulating ecosystem services individually (Table 4.12).

Table 4.12: The mean ecosystem service provision for individual tree species and study site tree population.

Tree species	**DBH** (cm)	**Carbon storage** (kg)	**Annual carbon sequestration** (kg/yr)	**Annual runoff avoided** (m^3/yr)	**Annual pollution removal** (g/yr)
Norway maple *(Acer platanoides)*	21.2	460.2	7.6	0.1	55.2
Sycamore *(Acer pseudoplatanus)*	116.2	4922.7	33.1	0.7	374.5
Horse chestnut *(Aesculus hippocastanum)*	3.8	1.5	0.6	0.0	14.4
Silver birch *(Betula pendula)*	21.6	183.1	8.5	0.0	17.7
Butterfly-bush *(Buddleja davidii)*	10.0	16.5	3.0	0.0	17.0
Hornbeam *(Carpinus betulus)*	25.6	153.8	6.9	0.1	41.5
Hawthorn *(Crataegus monogyna)*	43.8	1134.4	17.7	0.1	64.9
Broom *(Cytisus scoparius)*	15.8	47.8	6.4	0.0	11.5
Common ash *(Fraxinus excelsior)*	72.8	2579.5	17.5	0.6	316.9
Wilson holly *(Ilex x altaclarensis)*	83.8	2685.0	47.4	0.1	54.6
Apple spp. *(Malus)*	3.8	1.2	1.0	0.0	5.9
Crab apple *(Malus sylvestris)*	34.3	239.6	18.7	0.1	30.7
White poplar *(Populus alba)*	35.3	1285.7	12.4	0.1	66.7
Plum spp. *(Prunus)*	7.6	10.9	3.1	0.0	4.9
Wild cherry *(Prunus avium)*	91.5	4081.4	46.7	0.4	235.3
Dog rose *(Rosa canina)*	19.7	78.4	5.9	0.0	16.4
Goat willow *(Salix caprea)*	24.9	368.7	9.4	0.0	35.5
Grey willow *(Salix cinerea)*	36.2	274.9	20.2	0.3	169.9
Bay willow *(Salix pentandra)*	19.1	179.9	8.6	0.0	30.2
Willow spp. *(Salix)*	12.3	52.6	4.4	0.0	22.6
Osier willow *(Salix viminalis)*	19.8	112.8	6.0	0.0	18.3
Whitebeam *(Sorbus aria)*	17.0	43.5	7.0	0.0	21.6
Large-leaved lime *(Tilia platyphyllos)*	134.1	5093.1	55.9	1.3	716.7
English elm *(Ulmus procera)*	134.1	7040.6	73.4	0.6	348.7
Study site					
East Lancs Paper Mill	20.8	160.8	7.8	0.1	31.0
Radcliffe High School	25.1	357.2	9.5	0.1	26.1
Bradley Fold Trading Estate	16.5	139.7	9.0	0.1	30.3
Bolton Rd Park	120.6	5349.6	40.6	0.6	288.1

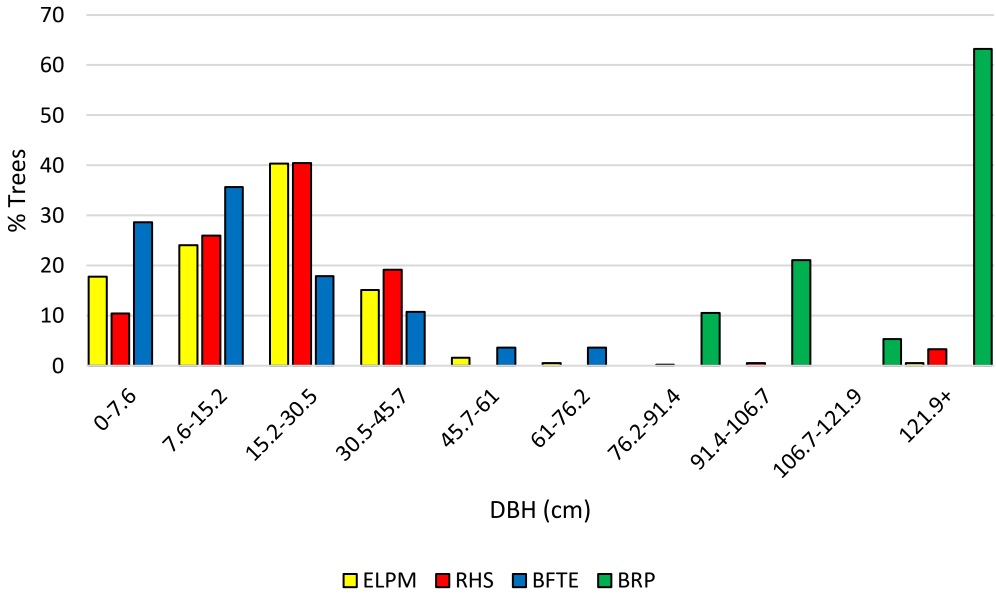

Figure 4.19: The distribution of study site trees DBH as an indicator of tree species maturity. Here i -Tree Eco DBH classes are used.

Figure 4.20 identifies the tree species at each site that provide the most ecosystem service benefits. In particular, *Betula pendula and Salix caprea* are significant providers of carbon storage and sequestration, air pollution removal, and runoff attenuation*.* *Betula pendula* is also the greatest provider of ecosystem services at all brownfield study sites. *Fraxinus excelsior* is the most beneficial tree at BRP in terms of ecosystem services.

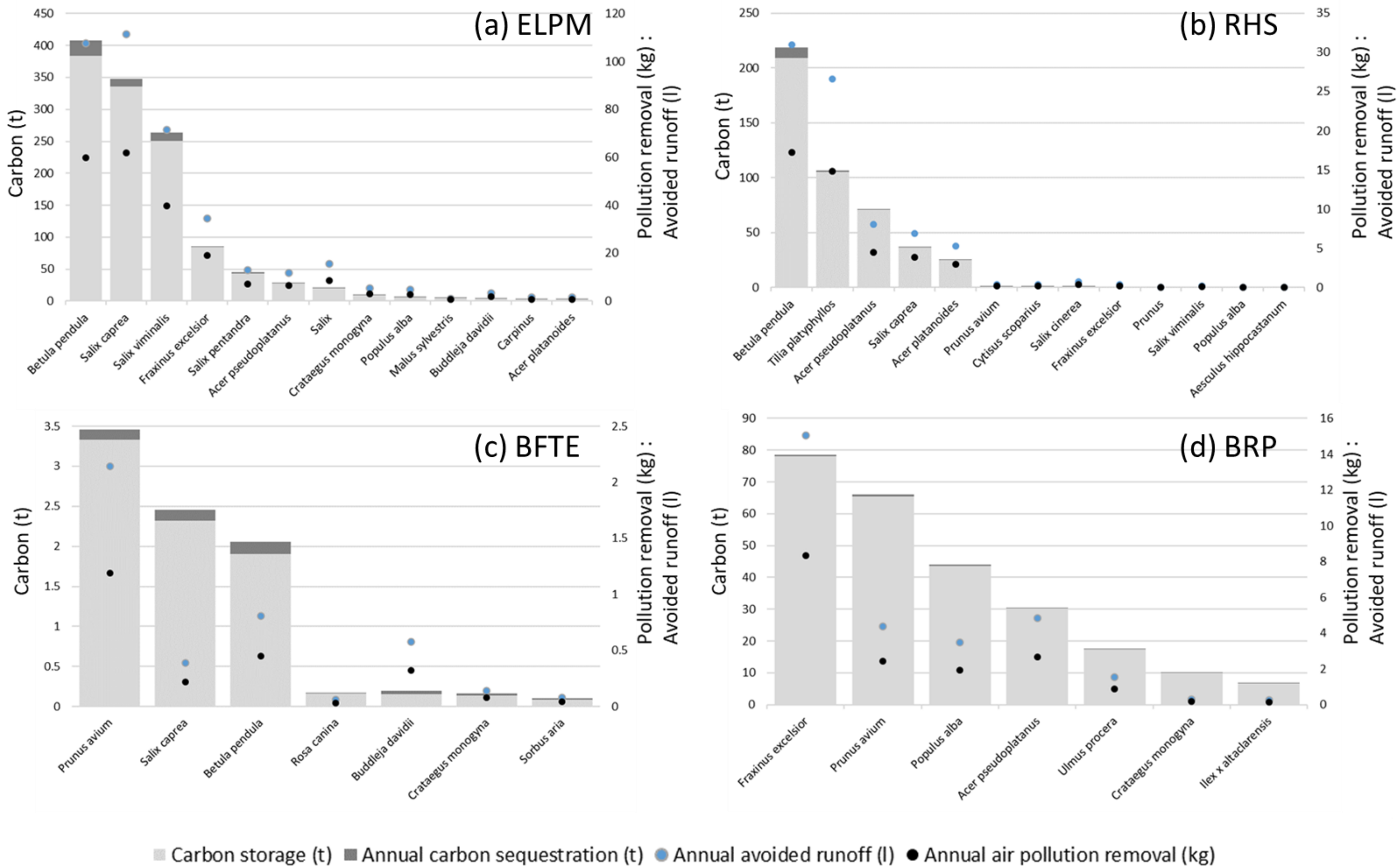

Figure 4.20: The ecosystem service provision by tree species for each study site. Fig. 4.20a East Lancashire paper mill site, Fig.4.20b Radcliffe high school site, Fig. 4.20c, Bradley Fold trading estate site, Fig. 4.20d Bolton Road park site.

4.4 Discussion

This study contributes to to existing knowledge by demonstrating the significant provision of regulating ecosystem services by urban brownfields. Results show that brownfield trees currently provide significantly more ecosystem services than parks in densely built urban areas (brownfield >5 times more ecosystem services). The i-Tree Canopy model estimated significant annual removal rates for air pollutants in urban areas compared to parks (56.7 t to 11.0 t). Although it is important to note that the potential removal rates depend upon the actual levels of ambient air pollution, the exposure of the trees, and individual tree species (Nowak, 2002). Road traffic is estimated to be the source of approximately 50% of urban air pollutants, in particular PM and NO_2 (Cox & Goggins, 2018), and evidence has suggested that vulnerable societal groups, such as school pupils (Sunyer et al., 2015) and socio-economically deprived communities (Makri & Stilianakis, 2008) may be disproportionally at risk from air pollutants due to urbanity and proximity to road networks (Makri & Stilianakis, 2008; Sunyer et al., 2015).

In this respect, brownfield urbanity, spatial heterogeneity (Holt, Mears, Maltby, & Warren, 2015), and proximity to transport networks (Brantley, Hagler, Deshmukh, & Baldauf, 2014; Janhäll, 2015b) should be seen as positive attributes of highly productive brownfields. The city wide distribution of brownfields (Escobedo & Nowak, 2009), and proximity to primary pollution sources (Gorman, 2003), increases efficiency of dispersion and deposition of air pollutants (Janhäll, 2015b). Additionally, Vieira et al. (2018) found that complex vegetation structures on unmanaged spaces like these, have a higher capacity to remove air pollutants in built-up areas. This capacity may be lost due to high rates of redevelopment in urban centres.

Whilst avoided runoff by trees in urban brownfields is greater than in parks (24,459m^3 to 4,731m^3), this may not be a representative measure, as other pervious surfaces can reduce surface water runoff in urban areas. For example, as the typology highlights that most types of park (11/12) are highly pervious (>60%) irrespective of tree canopy cover, whilst brownfield may commonly contain relatively high canopy cover surrounding a highly impervious site (e.g. hard surface with peripheral vegetation). Natural pervious surfaces exposed to precipitation will displace approximately 10% as surface water run-off (Arnold Jr & Gibbons, 1996), woodland loses approximately 13% as run-off (Bonan, 2015), whereas concrete or tarmac approximately 55% becomes surface water run-off (Arnold Jr & Gibbons, 1996). This highlights the significance of parks for attenuating surface water runoff, though also that losing highly vegetated urban brownfield to impervious development, where park land is scarce, needs consideration and trade-offs made where possible. Brownfields offer significant land area and opportunities for conversion into green infrastructure flood mitigation solutions in these areas (Dhakal & Chevalier, 2017; Song et al., 2019).

Carbon storage and sequestration by brownfields and parks for Greater Manchester was estimated to be 51,888t of carbon stored and 16.42t sequestered anually by brownfield trees, and 143,046t carbon stored and 34.65t sequestered by park trees. In urban areas only, brownfields store and sequester >5 time more than parks. However, it must also be noted that carbon storage and sequestration by urban green infrastructure is generally low when compared to a city's carbon emissions (Elmqvist et al., 2016). Statistics reported for Greater Manchester in 2017 state that the 10 combined GM districts produce CO_2 emissions totalling 12,165kt (DBEIS, 2019). Based on the i-Tree Canopy results, the total CO_2 stored in brownfield and park trees is equal to 1.56%, and 4.31% of the Greater Manchester annual CO_2 emissions respectively, with potential to sequester a further 0.06% by brownfield trees, and 0.17% by park trees annually. Nevertheless, these results provide an insight into carbon stores for a largely unrecognised source.

There is a substantial contrast between urban brownfield and urban park extent (1102 ha to 54 ha) and ecosystem service provision in urban areas (in Greater Manchester). This emphasises the importance of acknowledging ecosystem service provision at brownfield sites before redevelopment, but also highlights the lack of parks space in urban areas (area 1.3% urban, 16.7% suburban, 82% peri-urban area, and site centroid 8.4% urban, 48.7% suburban, 42.9% peri-urban) in Greater Manchester. Similar to other studies, the geographic distribution of parks in Greater Manchester is uneven (Oh & Jeong, 2007), with areas where park supply is low having high demand for ecosystem service provision, and vice-versa (Ji et al., 2020). Additionally, size, (availability of) recreational facilities, and landscape features have been shown to be important features of a park typology (Swanwick et al., 2003). These findings suggests that brownfield, with strategic planning, could provide additional open park space in urban areas.

Another key finding is the potential of brownfield for providing ecosystem services in urban areas. By examining the plantable space and maximum output of brownfield canopy cover suggests that, in areas where parks are absent, that converting brownfield to urban green infrastructure would significant increases in regulating ecosystem service provision (C stored 84,686t, C seq 3,372t, air pollution removed 503t, avoided runoff 216,841m^3). The scenario analysis showed a potential 797% increase in urban ecosystem service provision if all brownfields were converted to urban woodland. Employment of the micro-forest concept (Miyawaki, 1998), could significantly increase urban ecosystem service provision. The key factor in the creation of a micro-forest is the introduction of densely planted, local species (Miyawaki, 1998), and results show here that brownfields are already spontaneously populated with dense, native, and rapid pioneer tree species on disturbed substrates (Fig. 4.21). This means little intervention would be needed to install or enhance this specific type of green infrastructure on urban brownfields.

Figure 4.21: A dense woodland of Betula pendula up to 8m tall has established in 8 years on the RHS site. Source: Authors image, 2019.

Several distinct types of brownfield are highlighted as significant providers of ecosystem services when compared to parks. Irregular shaped and vegetated, densely vegetated, vegetated with water body, and uneven and vegetated sites (Fig. 4.22) contain superior tree canopy cover per hectare than other brownfield and several park types, and consequently provide significantly more ecosystem services. These discrete types of brownfield are revealed to be widely distributed across urban zones, and cumulatively occur in greater numbers than other brownfield and parks. These areas have most likely proven difficult to redevelop (or access) in the past (Nogués & Arroyo, 2016; Northam, 1971; Pagano & Bowman, 2004), allowing advanced stages of natural succession to establish (Gilbert, 1995; Kamvasinou, 2011; Wheater, 1999). However, these sites, left behind whilst the city has built up around them, are now under threat of development (Kamvasinou, 2011; Németh & Langhorst, 2014), especially with the brownfield-first approach to development in the study area (Greater Manchester Combined Authority, 2019b).

However, as Steinacker (2003, p. 495) states, “undeveloped land is undeveloped for a reason”, and problems with these distinct types of brownfield can mean higher risk and less lucrative projects for developers. A particularly fitting statement for these areas, although originally referring to urban open spaces, is by Lynch (1995, pp. 400 from Kamvasinou, 2011), who states “a network of relatively small spaces, well distributed within the urban system, may be more useful than the large tracts which look so well on land use maps”. The network of spaces Lynch refers to could easily be seen to contain these highly vegetated brownfield sites, especially in Greater Manchester. Their fragmented distribution, and status as less likely to be developed, supports climate resilience through extended carbon storage and sequestration (Mitchell et al., 2015).

*Figure 4.22: Highly ecosystem service productive brownfields. **(a)** a typical irregularly shaped site left unused between residential developments from different time periods. Image: (Getmapping, 2018). **(b)** An enclosed ‘densely vegetated site’ (with plans for30 residential dwelling) has developed an urban woodland of Betula Pendula and Salix caprea. Source: Author’s image, 2017. **(c)** a disused millpond surrounded by dense vegetation. Image: (Getmapping, 2018). **(d)** a disused railway track, purchased by a developer in 2020, with steep sides has developed a dense vegetation community with Betula pendula prominent. Source: Authors image, 2019.*

The significant area and ecosystem benefits provided by the brownfield type 'large dilapidated industrial or commercial' which are almost entirely located in urban zones, provide enormous potential to retain or enhance urban ecosystem service provision when redeveloped strategically and retain or install green infrastructure. Previous research has focused on the identification, selection and potential of brownfield for redevelopment, where the environmental focus is on remediating contamination and pollution (Bacot & O'Dell, 2006; Thomas, 2002), and other positive environmental attributes are rarely considered. However, results here demonstrate that more attention should be placed on the potential of brownfield as green infrastructure, particularly where other components of green infrastructure are lacking.

As an example, one such site in Greater Manchester has become the first large-scale city centre development to introduce a new city centre park for the first time in over 100 years (U and I Group, 2021). The Mayfield development is a large dilapidated industrial brownfield site in Manchester city centre and planners have consent to install a 2.6 ha park as part of the redevelopment process (U and I Group, 2021), demonstrating the potential retention of urban brownfield benefits even if the site is redeveloped (De Valck et al., 2019). Conversely, if unsuitable for redevelopment, even a contaminated brownfield can still supply significant ecosystem services to urban areas whilst simultaneously phyto-remediating the land (French, Dickinson, & Putwain, 2006).

The structure and composition of brownfield trees are a significant factor in their ecosystem service provision and are a niche urban ecosystem. The key finding here is the density and domination, of the selected previously disturbed brownfields, by two genera of tree, *Betula* spp. and *Salix spp.* The most abundant species were *Betula pendula, Salix viminalis* and *Salix caprea* which collectively account for 86% of the identified tree species on the brownfields. Similar to results shown here, recent studies have revealed *Betula pendula* to be one of the most important medium stature tree species, having a significant capacity to store and sequester carbon, remove air pollution and reduce stormwater runoff (Hand, Doick, & Moss, 2019). This high performance is mirrored in other studies for carbon sequestration (Uri et al., 2012) and particulate matter deposition by *Betula pendula* (Sæbø et al., 2012).

Furthermore, the structure and composition of tree species on brownfield sites when compared to parks promote further potential ecosystem service provision. The unmanaged self-seeding brownfield species which grow rapidly (up to 1m/yr) (Gilbert, 1995), are likely to have a much greater tree density than managed urban park trees, residential areas (Hall, 2010), and street trees (Taylor, Wheeler, White, Economou, & Osborne, 2015). Results observed the RHS brownfield site to be more than twice as efficient at carbon storage and sequestration, air pollution removal and avoided runoff than BRP, despite its similarity in area. Whilst *Betula pendula* and *Salix caprea* are dominant on brownfield, they are represented on several other land use types (**Appendix 4.3**); though these species rarely account for more than 10 percent of tree composition. The reasons for this are likely to include selective species planting on many urban land use types because of space constraints, pedestrian clearance, aesthetic qualities, and to limit maintenance and risks to the public through leaf litter or branch drop (Conway & Vander Vecht, 2015).

However, it must be noted that an individual mature, large stature tree found in the urban park (DBH >76cm) is significantly more beneficial in terms of these ecosystem services when compared to a young pioneer species occurring on a brownfield site (DBH <30cm) (Nowak, 1994), though carbon storage can level off and sequestration decreases as full maturity is reached (Nowak et al., 2013). This research is not suggesting that brownfields are more beneficial to cities and their residents than urban parks, but that they play an important role in the provision of urban ecosystem services provision, depending on the site condition, and substrate exposure after abandonment (Gilbert, 1995; Schadek et al., 2009).

The evidence presented here emphasises the importance of disturbed brownfield for the provision of ecosystem services in urban areas, as their characteristic species are unlikely to be found in similar quantities or densities on other urban land use types, and it is important to emphasise this as brownfield redevelopment intensifies. As an example here, the case study sites ELPM and RHS are estimated to contain 3750 *Betula pendula*, 2200 *Salix viminalis*, and 1360 *Salix caprea*, many of which will be removed due to the planned redevelopment of these sites for residential purposes (Bury Council, 2017; Deloitte, 2020). This highlights that the increase in brownfield redevelopment has stark implications for ecosystem service provision in urban areas (Davies et al., 2011a).

4.5 Limitations

With regard to the methods, tools and data used in this study, some limitations should be acknowledged. First, the quality of existing geospatial datasets utilised in analysis may not always encompass all data for a specific area, for example brownfields and parks may exist that have not been identified in the data. This was improved by the creation of an updated brownfield spatial dataset (**Chapter 3**), and sourcing the park data from the Ordnance Survey, a reputable source. Second, site access constraints restricted options for the case study sites. This was addressed by contacting local authorities who own multiple brownfield sites, resulting in diverse, accessible cases study sites located in the same locality.

Third, the use of i-Tree tools means that only trees and tree canopy cover were evaluated to estimate ecosystem service provision. Soil, water, and herbaceous vegetation also contribute to urban ecosystem services; however, trees are the most significant contributor of ecosystem service provision in urban land uses (Elmqvist et al., 2016; Livesley, McPherson, & Calfapietra, 2016). Fourth, the selection of weather and pollution monitoring stations available in i-Tree means that the source of some data used was remote from the study areas constraining the accuracy of estimated ecosystem service benefits. However, the acquisition of localised data would have required extensive work outside the scope of this research and the closest and most complete weather and pollution monitoring stations were selected. Fifth, there is also potential for human recording errors during the data collection and input phases, and classification methods, in particular the selection of training samples and identification of tree canopy (in i-Tree Canopy), relied upon personal image interpretation. Other potential for misclassification can include user error, parallax errors (images not taken from directly above), cloud cover, image quality, and excessive shadow in a scene (Campbell, 2006; Kaspar et al., 2017). Furthermore, whilst this research focuses on the benefits of brownfields and compares regulating ecosystem services between brownfield and parks, it is important to highlight the benefits of park use and the prescribing of park use for maintaining and improving mental health and wellbeing of individuals and communities (Lee & Maheswaran, 2011).

Chapter 5: Exploring brownfield, social vulnerability, and environmental hazards

5.1 Introduction

Improving urban resilience, protecting against climate and environmental hazards, and safeguarding the most at-risk or vulnerable populace are priority targets for cities (Defra, 2018; European Commission, 2013; UN-Habitat, 2020). As such, the investigation of environmental implications for the most vulnerable, in areas faced with increasing urbanisation, and substantial changes to land use and land cover, is becoming progressively important for hazard alleviation, and urban adaptation and resilience (Jennings et al., 2012; Rufat et al., 2019). Thus, over the past few decades, sustainable urbanisation has been a focus in post-industrial cities (Chen et al., 2009). Most notably, in the UK the principal focus of these development strategies, and also inherently linked to urban areas (through urban planning policy), is brownfield land (Oliver et al., 2005).

Densely built-up urban areas can contain highly concentrated populations and complex socio-economic and demographic systems. Furthermore, urbanisation and its associated increases in artificial surfaces, industry, energy use, transport activity and networks can also lead to increased environmental hazards (Barton, 2009; Wilby, 2007). Important hazards include, decreased air quality (Mayer, 1999), increased risk of flooding (Miller & Hutchins, 2017; Schreider et al., 2000), and increased urban ambient air temperatures, and the urban heat island effect (UHI) (Oke, 1973), which can impact the health and wellbeing of the population (Cutter et al., 2003; McMichael et al., 2003; Wilby, 2007). Exposure to increased environmental hazards such as these can disproportionately impact the most vulnerable communities in urban surroundings who are less able to prepare, respond, or recover to an event (Cutter et al., 2003).

Previous research has investigated the association between environmental hazards and the most socially vulnerably population. These studies have investigated, flooding (Chakraborty et al., 2020; Garbutt et al., 2015; Sayers et al., 2018; Tapsell et al., 2002), air pollution (Bae et al., 2019; Curtis et al., 2006; Ge et al., 2017; Makri & Stilianakis, 2008), and excessive urban heat (Kazmierczak, 2012; Mitchell, 2017). However, Cutter et al. (2003) noted that social vulnerability was not only attributable to social inequalities, but also a result of spatial or place inequalities, i.e. conditions of the built environment and interactions with vulnerable communities. This has led to the exploration of the links between social vulnerability and environmental hazards as well as elements of the built environment that can influence the risk of exposure for the vulnerable. Research incorporating elements of the built environment into social vulnerability research, has identified positive or negative influences of different urban land uses (e.g. green space or transport infrastructure) (Kaźmierczak & Cavan, 2011; Lindley et al., 2006). The relationship between brownfield and social vulnerability is hitherto relatively unstudied. Furthermore, the spatial dependency between brownfield and at-risk communities from a socio-ecological perspective is not understood and is not adequately addressed by the current body of literature. Furthermore, the potential of brownfield land to reduce the risk of exposure to environmental hazards from a socio-ecological perspective is currently unknown.

This chapter addresses these gaps, focussing on research **Objective 3** to investigate the spatial dependency between brownfield and at-risk communities and make recommendations for the most effective use of brownfield land to enhance urban resilience. To further understand how brownfield can contribute to urban resilience, specifically, this chapter will explore the relationship between three components; brownfield, social vulnerability, and environmental hazards in Greater Manchester at a neighbourhood scale. Kelly and Adger (2000, p. 328) define social vulnerability as the "ability or inability of individuals and social groupings to respond to, in the sense of cope with, recover from or adapt to, any external stress placed on their livelihoods and well-being". Thus, the concept of social vulnerability has associations with the concepts of risk (the likelihood of a hazard event impacting a social system) and degree of resilience (the ability of individuals or communities to resist, endure, adapt, recover from exposure to a hazard). Vulnerability, hazard, and exposure form the three components of risk, conceptualised in the risk triangle (Crichton, 1999) (Fig. 5.1), a widely used framework to assess social vulnerability in the context of environmental hazards (Birkmann, 2006; Dwyer, Zoppou, Nielsen, Day, & Roberts, 2004; Kaźmierczak & Cavan, 2011). Each side represents either hazard, exposure, and vulnerability, where increases, or decreases, in any one of these components influences risk (Crichton, 1999). For example, an increase in exposure increases the probability of harm, loss or damage by a hazard; similarly, if vulnerability decreases, then the probability of harm, loss or damage from a hazard decreases, and if any one component is zero then risk is absent (Crichton, 1999; Wolf, 2012).

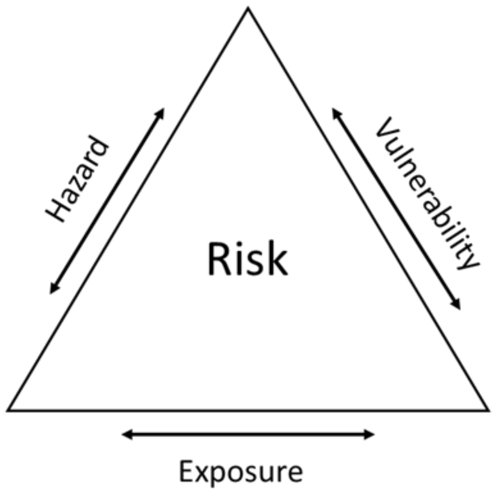

Figure 5.1: The risk triangle concept. Source: (Crichton, 1999).

To understand the relationship between brownfield and at-risk communities, social vulnerability to environmental hazards will be investigated. The degree of vulnerability or resilience (the opposite of vulnerability (Lindley et al., 2011)) of individuals or communities, or the ability to prepare, respond and recover have been linked to several socio-economic and demographic dimensions of social vulnerability which are a complicated and multi-faceted network (Cutter et al., 2003). To understand the spatial variances of social vulnerability and its dimensions is imperative to ensure a reduction in exposure and harm through targeted adaptation and resilience strategies.

Brownfield is considered a part of the built environment, thus its spatial and physical status and relationship to environmental hazards and social vulnerability may influence the level of exposure. Based on this, it is imperative to assess whether the extent, quantity, location, and specific types of brownfield, have the potential to affect human exposure to environmental hazards. Furthermore, where brownfields are located in areas where vulnerability, exposure, and hazard coincide, whether their current of future status may reduce risk of harm or loss. This research is important to better understand the potential positive or negative impacts of urban redevelopment processes utilising brownfield, and whether strategic redevelopment or modification of brownfields may potentially benefit these areas. In effect, this enables the adoption of strategic redevelopment opportunities based on socio-ecological status of brownfield in areas of increased social vulnerability, and environmental hazard exposure.

Consistent with **Chapter 4**, this research will focus on two environmental hazards that are important issues in urban areas: air pollution and flooding. Research has highlighted the increased risk of flooding from surface water flooding in built up areas with greater prevalence of impervious surfaces in comparison to rural areas (Bruwier et al., 2020; Douglas et al., 2010; Falconer et al., 2009; Kaźmierczak & Cavan, 2011; Smith & Lawson, 2012). River and coastal flooding places approximately 2.4 million properties at risk, most of which are in urban areas, and this is likely to increase in the future (Environment Agency, 2009; Miller & Hutchins, 2017). Incidents of flooding can cause both physiological and physical strain to the populations impacted (Gill, 2006), especially the elderly, the young, and those with existing health conditions or living in areas of social and economic deprivation (Lindley et al., 2011; Pelling, 2012).

Air pollution has widespread health impacts (Colls, 2002), and in the UK is estimated to contribute approximately 40,000 deaths annually (2016 data) (Royal College of Physicians, 2016). However, increases in transport and population in the post-war period have led to increased exposure of inhabitants to air pollution (Colls, 2002). It is widely recognised that air pollution has a negative impact on respiratory and cardiovascular health (Brunekreef & Holgate, 2002; Schwela, 2000), and is a long established policy issue, dating back to the 1956 Clean Air Act (Royal College of Physicians, 2016). Furthermore, several studies have linked increased air pollution exposure and consequences with socially vulnerable populations in urban areas increasing poor health and mortality rates (Benmarhnia et al., 2014; Jerrett et al., 2004; Makri & Stilianakis, 2008). The currency and amount of importance placed on both air pollution and flooding for Greater Manchester (Brisley et al., 2018; Clean Air Greater Manchester, 2020; Cox & Goggins, 2018; Greater Manchester Combined Authority, 2018, 2019a, 2019c), and consistency with **Chapter 4** ecosystem service analysis is the rationale for the selection of these environmental hazards.

Thus, this research addresses a significant gap in the knowledge concerning the current understanding of how brownfield or its redevelopment may influence the exposure of at-risk communities to environmental hazards. Furthermore, identifying spatial aspects of social vulnerability, hazards and exposure in the built environment may inform of brownfield which may help reduce long term exposure to environmental hazards via ecosystem service provision, and aid the reduction of risk to the socially vulnerable through their preservation or modification. There is a paucity of research exploring the potential of brownfield to attenuate flooding and/or air pollution exposure. There are no (known) current studies examining the relationship between social vulnerability, brownfields, and multiple environmental hazards, applying a brownfield typology at a neighbourhood scale.

5.1.1 Chapter aim and structure

The principal aim of this chapter is **to investigate the spatial dependency between brownfield and at-risk communities and make recommendations for the most effective use of brownfield land to enhance urban resilience**. This chapter is structured as follows. **Section 5.2** presents the methods including; analysis of dimensions of social vulnerability and construction of a composite index within Greater Manchester, the mapping of environmental hazards, the investigation of the spatial and statistical relationships between brownfields, social vulnerability, and environmental hazards**,** and the creation of environmental indicators to apply to statistical results. The results of the analysis are then described in **Section 5.3**, including a social vulnerability index (**5.3.1**), air quality and flood maps (**5.3.2 and 5.3.3**), cluster maps created using spatial autocorrelation (**5.3.4**), and statistical relationships (**5.3.5**). Finally, **Section 5.4** discusses the key findings, and **Section 5.5** describes some limitations of the research.

5.2 Methods

To explore brownfield, social vulnerability, and environmental hazards in Greater Manchester, and identify brownfield sites to aid urban resilience, a multi-step quantitative methodology is undertaken. Specifically, **(i)** the analysis of social vulnerability in Greater Manchester, **(ii)** the exploration of the spatial distribution environmental hazards, **(iii)** the investigation of the spatial and statistical relationship between brownfield, social vulnerability, and environmental hazards, specifically flooding and air pollution.

- To analyse social vulnerability and its dimensions, a composite index of social vulnerability is created using Principal Component Analysis (PCA) and mapped across Greater Manchester.
- The investigation of the spatial distribution of environmental hazards is undertaken in GIS using existing environmental hazard data and thematic mapping.
- Exploratory spatial analysis of the relationship between brownfield, social vulnerability and environmental hazards is undertaken using Moran's I, Local Indicators of Spatial Association (LISA), and bivariate LISA (BiLISA) statistics.
- The investigation of the statistical relationship between different types of brownfield, social vulnerability, and environmental hazards is carried out using Spearman's rank order correlation and regression analysis.

- To identify types of brownfields that currently or potentially increase urban resilience to environmental hazards, ecosystem service indicators are created and applied to statistical results.

All data and spatial analysis was undertaken in ArcGIS (version 10.7.1), GeoDa (version 1.14.0) and SPSS (version 26).

To aid visualisation and interpretation of the spatial distribution of brownfield, social vulnerability and environmental hazards, a map of the urban, suburban, and peri-urban zones, along with the main town and city centres in Greater Manchester districts is provided in Figure 5.2.

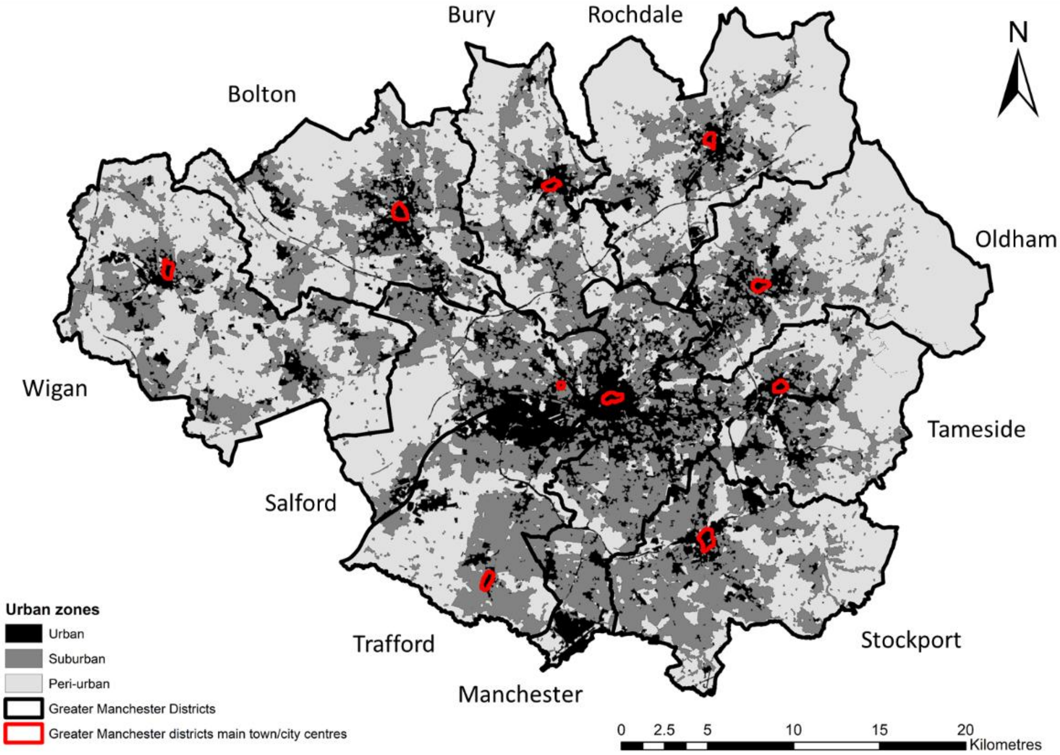

Figure 5.2: Greater Manchester urban zones and town/city centres. Base maps are © Crown Copyright/database right (2021). Urban zones from reclassified land cover map 2015 (Rowland et al., 2017) © NERC (CEH) EDINA Digimap Ordnance Survey Service. Town centres from (Ministry of Housing Communities and Local Government, 2020) no conditions apply.

The analyses were undertaken at Lower Super Output Area (LSOA) scale. LSOA are digital boundaries representing compact areas designed to report small area statistics for England and Wales (ONS, 2020) (Figure 5.3). There are 1,673 LSOAs in Greater Manchester each containing a minimum population of 1000 residents or 400 households, and a mean of 1500 individuals (600 households) (ONS, 2020). LSOA are valuable for neighbourhood analysis (Norman, 2016; Verhaeghe & Tampubolon, 2012), which offer a suitable analysis scale given the size of the study area. In addition, using LSOAs enables comparison with previous research in this study area (Kaźmierczak & Cavan, 2011), and are also widely recognised by UK local authorities, and employed in resource allocation and planning services (ONS, 2020).

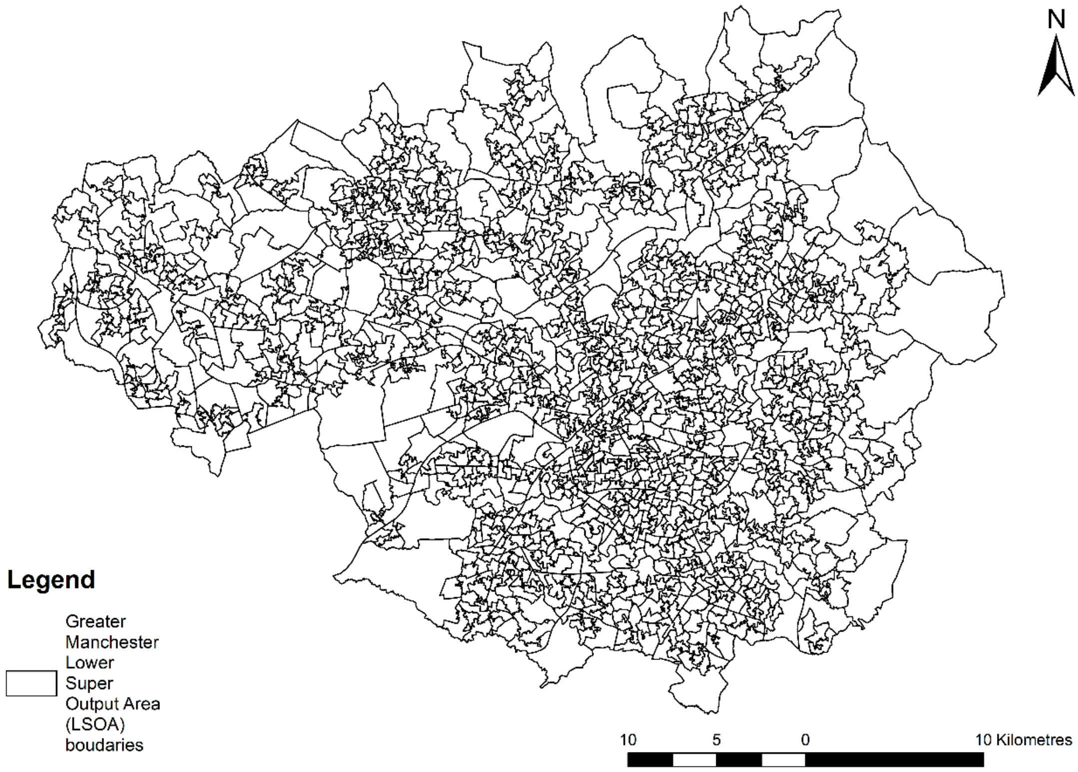

Figure 5.3: Lower super Output Area neighbourhood boundaries in Greater Manchester. Base maps are © Crown Copyright/database right (2021). An Ordnance Survey/EDINA supplied service. Greater Manchester LSOA boundary data, ONS (2021).

Brownfield data used in this analysis was generated in **Chapters 3 & 4** and is represented by the areal percentage of brownfield (and typology) within each LSOA unit. This cross-tabulates the intersection between the brownfield spatial databases (total brownfield, and typology) and the LSOA units to determine the proportion of each brownfield dataset within each LSOA polygon. The rationale for selecting brownfield area percentage of LSOA is that many sites lie across LSOA boundaries, whereas number of brownfields (e.g. based on site centroid) per LSOA could underestimate the impact of brownfield sites. Figure 5.4 illustrates the percentage of each LSOA occupied by brownfield in Greater Manchester.

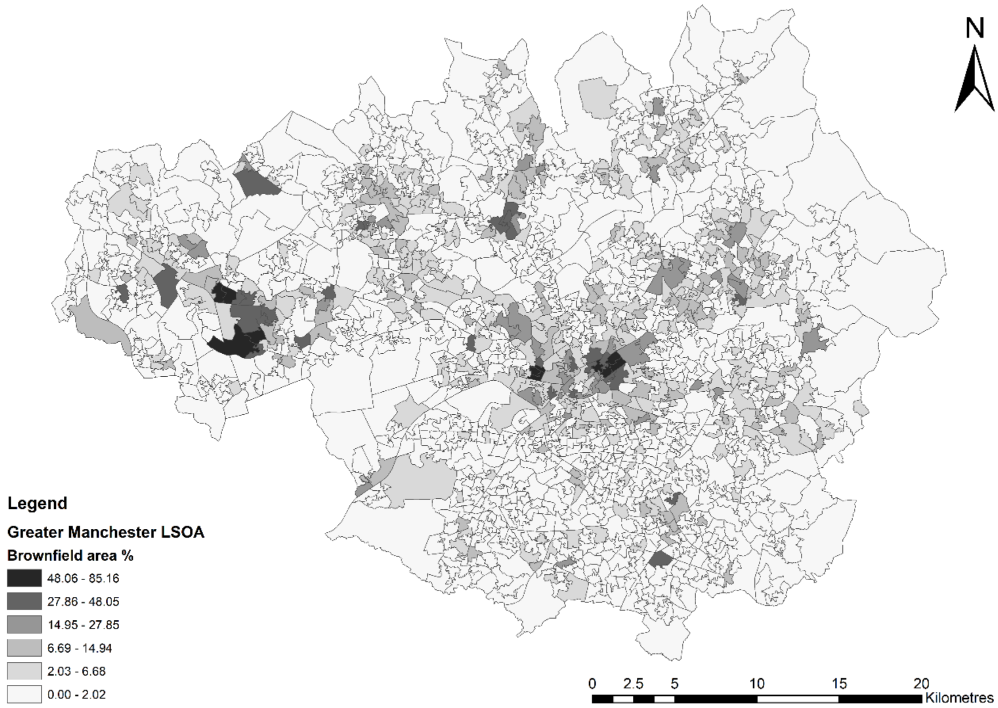

Figure 5.4: Brownfield area as a percent of LSOA territory. Natural breaks (Jenks) classification. Base maps are © Crown Copyright/database right (2021). An Ordnance Survey/EDINA supplied service. Greater Manchester LSOA boundary data, ONS (2021).

5.2.1 The creation of a composite index of social vulnerability

An indicator-based approach is employed to examine social vulnerability across Greater Manchester. This utilises a wide range of relevant and accessible indicators known to influence vulnerability, and which represent the established dimensions identified in previous studies (Cutter et al., 2003; Cutter et al., 2009; Fatemi et al., 2017; Kazmierczak, 2012; Lundgren & Jonsson, 2012; Otto, Otto, Reckien, Reyer, & Marcus, 2017; Reckien, 2018; Rufat et al., 2015; Rufat et al., 2019; Tapsell et al., 2010; Tapsell et al., 2002). To permit assessment of social vulnerability, the numerous influencing dimensions must be assigned measurable numeric variables (Garbutt et al., 2015), which encompass the geography and scale of analysis for the study area (Rufat et al., 2015). This indicator development process involves principal component analysis (PCA) of these variables to identify patterns and reveal underlying factors of social vulnerability within the study area (Cutter et al., 2003). Additionally these are then amalgamated and rescaled to produce a variance weighted composite index (Reckien, 2018).

A total of thirty-one direct or proxy indicators were identified which are representative of the common themes identified in previous studies (Table 5.1) and have numerical data variables available within the study area at the relevant scale. All data representing the indicators were acquired from the Indices of Multiple Deprivation 2019 (IMD2019) (Ministry of Housing Communities and Local Government, 2019a), and Office for National Statistics (ONS) (2020)

(Census 2011). These were the most current databases that are available at LSOA level within Greater Manchester which contain many demographic indicator variables representing population, age, health, race, sex, economic, deprivation, employment, education, built environment (MHCLG, 2019; ONS, 2020). The rationale for choosing the social vulnerability indicator variables are well established in most vulnerability to environmental, climate and natural hazards literature (Cutter et al., 2003; Cutter et al., 2009; Fatemi et al., 2017; Kaźmierczak & Cavan, 2011; Lee, 2014; Lindley et al., 2011; Rufat et al., 2019; Tapsell et al., 2010).

Table 5.1: Indicators of social vulnerability.

Indicators of social vulnerability	Year	Source	Theme	Data
Income Score (rate)	2019	IMD	Income	The proportion of population experiencing deprivation relating to low income
Employment Score (rate)	2019	IMD	Employment	The proportion of working age population excluded from the labour market
Income Deprivation Affecting Children Index (IDACI) Score (rate)	2019	IMD	Income, Age	The proportion of all children 0-15 living in income deprived homes
Income Deprivation Affecting Older People (IDAOPI) Score (rate)	2019	IMD	Income, Age	The proportion of all those aged 60+ living who experience income deprivation
Adult skills and English language proficiency indicator	2019	IMD	Education	A count of those adults with no or low qualifications, and/or who cannot speak English or cannot speak English 'well'
Household overcrowding indicator	2019	IMD	Physical environment, Living arrangements	The proportion of all households in a Lower-layer Super Output Area which are judged to have insufficient space to meet the household's needs
% People with no qualifications	2011	ONS	Education	Those over 16 with no qualifications
% people with no or level 1 qualifications	2011	ONS	Education	Those over 16 with no or level 1 qualifications
% Households with no adults in employment and dependent children	2011	ONS	Employment, Age	Those households with no adults in employment and the presence of dependent children
% Households with no adults in employment (no children)	2011	ONS	Employment	Those households with no adults in employment with no presence of dependent children
% Unemployed of economically active population (16-74)	2011	ONS	Employment	A person's economic activity is derived from their 'Activity last week' in the census. Whether employed, looking for work, waiting to start a job, available for work, or status if unemployed/seeking employment.
% Households with no vehicle	2011	ONS	Mobility	This applies to the number of cars or vans that are owned, or available for use, by one or more members of a household
People per hectare	2018	ONS	Population density	Data from Mid-2018 population estimates divided by area of LSOA's in England and Wales
% People 0-4 years old in the population	2018	ONS	Age	Derived from ages reported in Mid-2018 population estimates for LSOA's in England and Wales
% Population aged 5 to 17	2018	ONS	Age	Derived from ages reported in Mid-2018 population estimates for LSOA's in England and Wales
% Population aged 65-74	2018	ONS	Age	Derived from ages reported in Mid-2018 population estimates for LSOA's in England and Wales
% Population aged 75 and over	2018	ONS	Age	Derived from ages reported in Mid-2018 population estimates for LSOA's in England and Wales
% Households with dependent children under 5 years old	2011	ONS	Age	The proportion of households containing children under 5-year-old

% Households with dependent children 5–18 years old	2011	ONS	Age	The proportion of households containing dependent children between 5 and 18 years old
% Single person households with residents aged 65 or over	2011	ONS	Age, Living arrangements	The proportion of households containing single male or female occupants aged over 65 years old
% Single person households resident aged less than 65	2011	ONS	Age, Living arrangements	The proportion of households containing single male or female occupants aged below 65 years old
% Lone parent households with dependent children	2011	ONS	Age, Living arrangements	Census housing composition data for lone parent households with dependent children where the lone parent is aged 16 to 74
% Private rented	2011	ONS	Housing status	The proportion of population who reside in a private rented accommodation
% Social rented	2011	ONS	Housing status	The proportion of population who reside in a social rented accommodation
% Total rented	2011	ONS	Housing status	The proportion of population who reside in rented accommodation
% Ethnic Minorities	2011	ONS	Ethnicity	The proportion of population who are not UK based on their own perceived ethnic group and cultural background
% Households with no adult with English as main language	2011	ONS	Ethnicity, Education	No people aged 16 and over in household has English as a main language
% People born outside the UK	2011	ONS	Ethnicity	The proportion of people not born in the UK
% Households with at least one person with a limiting long-term illness	2011	ONS	Health	The proportion of households with an occupant with a long-term health problem or disability that limits day-to-day activities, and has lasted, or is expected to last 12 months
% Population whose self-reported health is not good	2011	ONS	Health	The proportion of population with fair, bad, and very bad self-reported health status in the census
% Population whose self-reported health is bad or very bad	2011	ONS	Health	The proportion of population with bad and very bad self-reported health status in the census

PCA is a mathematical technique which synthesises large amounts of data and rotates it onto new compound axes, explaining variance and reducing the data sets into its principal components, factors, or domains, with each variable having a factor loading (Abdi & Williams, 2010). The factor loading is the correlation of each variable on the corresponding principal component; in general the higher the loading, the higher the correlation and vice versa (Abdi & Williams, 2010). Furthermore, each principal component is uncorrelated and PC1 is more important than PC2, which in turn is more important than PC3 and so on, and the majority of information (variance within the original dataset) is displayed within the first few components. (Vyas & Kumaranayake, 2006). The primary assumption attained by utilising PCA is that a small number of fundamental components of the data can be used to explain complex relationships within numerous indicators (Vincent, 2004). In this analysis, the Kaiser criterion (Kaiser, 1960) was applied, thus components with eigenvalues greater than 1.0 were selected to represent the optimal number of components that can be used to describe the data, as eigenvalues less than 1.0 are not considered reliable (Jolliffe, 2002; Kaiser, 1960). Variables with a factor loading or correlation of greater than 0.5 represent that component (Jolliffe, 2002). This process selects components that account for more variance than the original individual variables (Wolf & McGregor, 2013). This analysis was carried out using statistical package SPSS 26.

Indicator data sets standardised due to the multiple scales and units of the indicators (Jolliffe & Cadima, 2016). The PCA utilised a varimax rotation, a commonly used rotation that results in each factor containing a small number of high loadings and a larger amount of low loadings, which simplifies the interpretation of the data, helping to highlight a small number of variables where component outputs all have eigenvalues greater than 1 (Abdi, 2003; Kaiser, 1958).

For each of the retained principal components (eigenvalue >1), the factor loading of each high loading variable (>0.5) was used to multiply the standardised variable (for each LSOA). Subsequently, these new variable scores are combined and rescaled on a zero to one scale using Equation 5.1, to produce a score for each principal component for each LSOA (Baum, Horton, & Choy, 2008; Langlois & Kitchen, 2001).

$$\boldsymbol{x'} = \frac{\boldsymbol{x - min(x)}}{\boldsymbol{max(x) - min(x)}} \qquad \textit{Eq. 5.1}$$

Where x is the original value and x' is the rescaled value.

Multiple components or dimensions of social vulnerability can be amalgamated to construct a composite index (Tate, 2012). A single index can filter the multifaceted structure of several un-associated dimensions (as identified in the PCA) into a single metric (Tate, 2012). In general, the construction of a social vulnerability index, after PCA has been undertaken, requires several steps, including factor retention (how many PC to keep), weighting of components (equal or otherwise), and combination (i.e. addition, multicriteria analysis or otherwise) (Reckien, 2018; Tate, 2012).

To construct a composite social vulnerability index, the PCA scores for each retained component and LSOA were weighted based on their percent of variance divided by the total variance of all extracted components, and summed (Solangaarachchi, Griffin, & Doherty, 2012; Wolf & McGregor, 2013). The composite index was rescaled to 0-1 (Eq. 5:1), representing extremely low (0) to maximum (acute) (1) social vulnerability. The creation and mapping of a weighted index considers all of the main components of social vulnerability allowing visualisation on one map, placing emphasis on those that were statistically more important in the PCA, and allowing assessment of social vulnerability over space and time (Garbutt et al., 2015; Tate, 2012).

The retained components and the composite index of social vulnerability was subsequently charted using choropleth maps, with a six-class equal interval classification to represent social vulnerability spatially for each LSOA. Equal interval classification allows ease of data interpretation emphasises class value relative to other values (Slocum, McMaster, Kessler, & Howard, 2009). Most effective map classifications use between four and six distinct classes (Slocum et al., 2009). Previous mapping of social vulnerability has represented social vulnerability using four (Garbutt et al., 2015), five (Frigerio & De Amicis, 2016; Ge et al., 2017; Kaźmierczak & Cavan, 2011; Kazmierczak, Cavan, Connelly, & Lindley, 2015) or six classes (Lindley et al., 2011; Scott et al., 2016). Here a six-class classification allowed ease of visualisation of the divergence of data above and below the mid-point in the rescaled vulnerability component scores (Brewer, 2005).

5.2.2 The distribution of environmental hazards

Analysis of hazard exposure includes flood hazard (river and/or surface water flooding) and air quality. Datasets used for analysing environmental hazards are presented in Table 5.2. The geospatial analysis of flooding and air pollution data using thematic mapping, will provide a value for air quality index deciles and percent of flood exposure in each LSOA in Greater Manchester. Creation of the flood exposure and air quality maps was carried out in ArcGIS (version 10.7.1).

Table 5.2: Datasets used for environmental hazard maps.

Hazard	Data set	Definition	Resolution /Scale	Version/Source
Flooding	Risk of Flooding from Surface Water (RoFSW)	Areas susceptible to surface water flooding 15CM and above with a 1 in 100 (1%) chance in any given year	2 metre	19-Mar-20, (Environment Agency, 2020)
	Flood Map for Planning (Rivers and Sea) - Flood Zone 3	Areas with a 1 in 100 (1%) or greater chance of flooding each year from rivers and the sea	2 metre	05-May-20, (Environment Agency, 2020)
Air pollution	Access to Healthy Assets and Hazards (AHAH)	Air quality deciles where 1 represents good air quality and 10 represents poor air quality	LSOA	Version 2, (Consumer Data Research Centre, 2019)
	English Lower Layer Super Output Areas, 2011	Digital boundaries representing compact areas designed to report small area statistics	Mean of 1500 individuals (600 households)	26-Aug-16, (ONS, 2011)

5.2.3.1 Flood exposure

Using a vector overlay operation, a flood hazard map for GM was created using UK river and surface water flood data from the Environment Agency (EA) (Environment Agency, 2020a, 2020b) (Table 5.2 & Fig. 5.5). The surface water flood dataset was processed to represent surface water flooding at a depth of 15 cm and above, as even shallow water depths can pose a risk to people, infrastructure, housing, and automobiles depending on water velocity (Houston et al., 2011; Pregnolato, Ford, Wilkinson, & Dawson, 2017; Royal Society for the Prevention of Accidents, 2020). The combination of these datasets presents a geospatial representation of any area exposed to river and/or surface water flood events (Fig. 5.5).

Figure 5.5: Pluvial and pluvial flood risk example. Fluvial and pluvial flood data: © Environment Agency copyright and/or database right 2021. LSOA boundary data: © Copyright 2018 UK Data Service. All rights reserved. This information is licensed under the terms of the Open Government Licence. All rights reserved. Buildings data: "Digital Map Data © The GeoInformation Group Limited 2019".

5.2.3.2 Air pollution exposure

The Healthy Assets and Hazards (AHAH) dataset (CDRC/University of Liverpool and UK Open Government License (OGL)) (Daras, Green, Davies, Barr, & Singleton, 2019; Green, Daras, Davies, Barr, & Singleton, 2018) was used to investigate air pollution exposure. The AHAH utilises a suite of indicators which are combined to measure accessibility and exposure to health-related features for LSOA level. It uses numerous indicators which are combined to create a multi-dimensional index (Green et al., 2018). The AHAH's physical environment domain data contains air pollution indicators including Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), and Particulate Matter < 10 µm (PM_{10}) for each LSOA sourced from DEFRA (Brookes et al., 2017; Daras, Davies, Green, & Singleton, 2018). Modelled estimates (2016) of each pollutant were extrapolated from 1500 monitoring sites into cells of 1km^2, taking into consideration the influence of pollution sources (Brookes et al., 2017).

This dataset has previously been used by government organisations such as Public Health England (2018), European Commission (Brookes et al., 2017), local authorities (Gloucestershire County Council, 2018) and researchers (Daras et al., 2019; Green et al., 2018). The mean modelled air pollutant data of each 1km^2 grid cell was calculated for intersecting LSOA (Daras et al., 2019). These were standardised and transformed to the standard normal distribution and combined with equal weights. This formed an overall air quality domain score before exponential transformation to create deciles was undertaken (Green et al., 2018). Thematic mapping using choropleth maps was undertaken to explore the spatial distribution of air quality and provides a value for each LSOA in Greater Manchester.

5.2.3 Spatial statistical relationships between brownfield, social vulnerability, and environmental hazards

To explore the spatial relationship, patterns between brownfield, social vulnerability, and environmental hazards, and identify the extent of clustering and location of clusters, Moran's I, Local Indicators of Spatial Association (LISA), and bivariate LISA (BiLISA) statistics are utilised. Moran's I is a common test for spatial autocorrelation (Tiefelsdorf, 2002). Global Moran's I compares how similar each value (within each LSOA) is to its neighbours to indicate positive, neutral, or negative values showing an overall spatial pattern (Bivand, 2010). LISA identifies areas with spatial clusters (LSOA with similar values) and dispersion (LSOA with dissimilar values) for a variable and the spatial lag of the same variable in nearby locations. BiLISA identifies spatial clusters and dispersion between one variable, and a second variable in nearby locations. LISA and BiLISA maps displays positive spatial correlation clusters (hotspots), expressed as High-High or Low-Low, and negative spatial correlation outliers (coldspots), expressed as High-Low or Low-High, in addition to locations that are not significant (Anselin, 2020). The spatial autocorrelation of brownfield, social vulnerability, and environmental hazards is examined in GeoDA (https://geodacenter.github.io/documentation.html), an open source spatial analysis tool to model spatial patterns (Anselin, Syabri, & Kho, 2010).

5.2.4 Statistical relationships between brownfields, social vulnerability, and environmental hazards

Spearman's rank order correlation was employed to determine the statistical relationship between brownfield types, social vulnerability, and environmental hazards for each LSOA neighbourhood (Dytham, 2011). Histograms and the Kolmogorov-Smirnov test found that the datasets had a skewed distribution. Spearman's rank order correlation, a non-parametric test, was therefore appropriate to test the strength of association between two variables (Kent & Coker, 1994). Further associations are explored using descriptive statistics and linear regression where the scaled data from the composite social vulnerability index was discretised or binned using equal intervals of the data range (Kotsiantis & Kanellopoulos, 2006). This allows the exploration of mean proportion of brownfield coverage at several levels of social vulnerability within the study area.

Two new indicators were constructed to aid the identification of specific types of brownfields that may present current or potential opportunities to increase urban resilience and make suggestions for implementing them. A Brownfield Ecosystem Service Index (BESI) and Brownfield Perviousness Index (BPI) are created for the brownfield typology. The BESI is the sum of four standardised values for each ecosystem service (carbon storage and sequestration, air pollution removal and avoided surface water runoff by trees) per hectare of brownfield type rescaled (equation 5.1, p.17) and assigned deciles using 10^{th} percentiles. The BPI is the mean pervious land cover % for each brownfield type which is rescaled and assigned deciles. These indicators were constructed similar other documented aggregate indicators, which combine individual ecosystem service data into one index (see (Dick, Maes, Smith, Paracchini, & Zulian, 2014; Maes et al., 2015; Maes, Paracchini, Zulian, Dunbar, & Alkemade, 2012)). This provided a visualisation aid to interpret the current or potential benefits of the brownfield typology should any spatial associations be identified in the statistical analysis. The indicators may be generalised as Low 1-3, Moderate 4-7, and high 8-10 when interpreting the results.

5.3 Results

5.3.1 Social vulnerability index

Four principal components of social vulnerability were identified using PCA which explained 85.4% of the variance in the data (Table 5.3). The components were named according to the high loading variables which were associated with them (factor loading >0.5) (Table 5.4). Socio-economic deprivation (PC1) was associated with low-income residents, unemployment, rented housing, low educational achievement, and poor health (Table 5.4). Population diversity (PC2) was most associated with high population density, ethnic minorities, household overcrowding, and ability to communicate in English. PC3, 'Youth', is associated with areas with high presence of households with children and youths. The final component is PC4, the 'Elderly', which is associated with older age groups, and households with no adults in employment and no children (Table 5.4). Similarly, earlier work in Greater Manchester, based on census 2001, identified these same four principal components of social vulnerability (Kazmierczak & Cavan, 2011).

Table 5.3: Principal component analysis: Total variance explained.

				Extraction Sums of Squared Loadings			**Rotation Sums of Squared Loadings**		
Component	**Initial Eigenvalues**	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**
1	14.4	46.5	46.5	14.4	46.5	46.5	12.4	40	40
2	6.5	21.1	67.6	6.5	21.1	67.6	6.4	20.5	60.6
3	3.8	12.3	79.9	3.8	12.3	79.9	4.3	13.8	74.4
4	1.7	5.5	85.4	1.7	5.5	85.4	3.4	11	85.4

The extracted components with an eigenvalue > 1

Table 5.4: Principal component (PC) loadings for each social vulnerability indicator. Significant loadings for each variable on each component are in bold/grey fill.

Rotated Component Matrix	**Principal components**			
	Socio-economically deprived (PC1)	**Population diversity (PC2)**	**Youth (PC3)**	**Elderly (PC4)**
Income Score (rate)	**0.914**	0.285	0.219	-0.033
Employment Score (rate)	**0.95**	0.138	0.126	0.04
Income Deprivation Affecting Children Index (IDACI) Score (rate)	**0.886**	0.225	0.115	-0.169
Income Deprivation Affecting Older People (IDAOPI) Score (rate)	**0.671**	0.627	0.134	-0.044
Adult skills and English language proficiency indicator	**0.86**	0.118	0.362	0.047
% People with no qualifications	**0.891**	-0.002	0.27	0.224
% People with none or level 1 qualifications	**0.863**	-0.11	0.332	0.17
% Households with no adults in employment with dependent children	**0.763**	0.273	0.432	-0.236
% Unemployed of Economically active population (16-74)	**0.862**	0.236	0.2	-0.144
% Households with no vehicle	**0.785**	0.54	-0.164	-0.124
% Single person households resident aged less than 65	**0.501**	0.437	-0.517	-0.283
% Lone parent households with dependent children	**0.758**	-0.063	0.396	-0.345
% Social rented	**0.901**	0.145	0.056	-0.089
% Total rented	**0.724**	0.497	-0.214	-0.328
% Households with at least one person with a limiting long-term illness	**0.818**	-0.071	0.158	0.468
% Population whose health is not good	**0.859**	-0.089	-0.009	0.419
% Population whose health is bad or very bad	**0.905**	0.033	-0.011	0.269
Household overcrowding indicator	0.181	**0.808**	-0.303	-0.307
People per hectare	0.03	**0.635**	0.006	-0.204
% Private rented	-0.095	**0.65**	-0.458	-0.439
% Ethnic Minorities	0.068	**0.917**	0.306	0.008
% Households with no adult with English as main language	0.118	**0.937**	0.203	-0.03
% People born outside the UK	0.077	**0.957**	0.158	-0.049
% People 0-4 years old in the population	0.278	0.15	**0.501**	-0.046
% Population aged 5 to 17	0.337	0.059	**0.844**	-0.054
% Households with dependent children under 4 years old	0.283	0.294	**0.81**	-0.245
% Households with dependent children 5–18 years old	0.117	-0.045	**0.949**	-0.173
% Households with no adults in employment (No children)	0.493	-0.054	-0.298	**0.738**
% Population aged 65-74	-0.325	-0.632	-0.089	**0.543**
% Population aged 75 and over	-0.267	-0.437	-0.143	**0.734**
% Single person households resident aged 65 or over	0.236	-0.278	-0.18	**0.783**

The four principal components of social vulnerability each display a unique spatial pattern. Areas with higher-than-average socio-economic deprivation (PC1) tend to occur close to district centres and their suburbs (Fig 5.6a). Population diversity (PC2) is most prominent in the regional centre, extending both North and South from Manchester city centre, extending into suburban areas (Fig. 5.6b). Some clustering is also evident around northern district centres; however, most of the conurbation displays extremely low population diversity. The youth component (PC3) mostly displays high prominence in suburban areas, and some isolated LSOA (Fig. 5.6c). The elderly component (PC4) is more heterogeneous in its distribution than the other principal components, with higher scores mostly in peri-urban and suburban areas, and evidently lower scores in urban centres (Fig 5.6d).

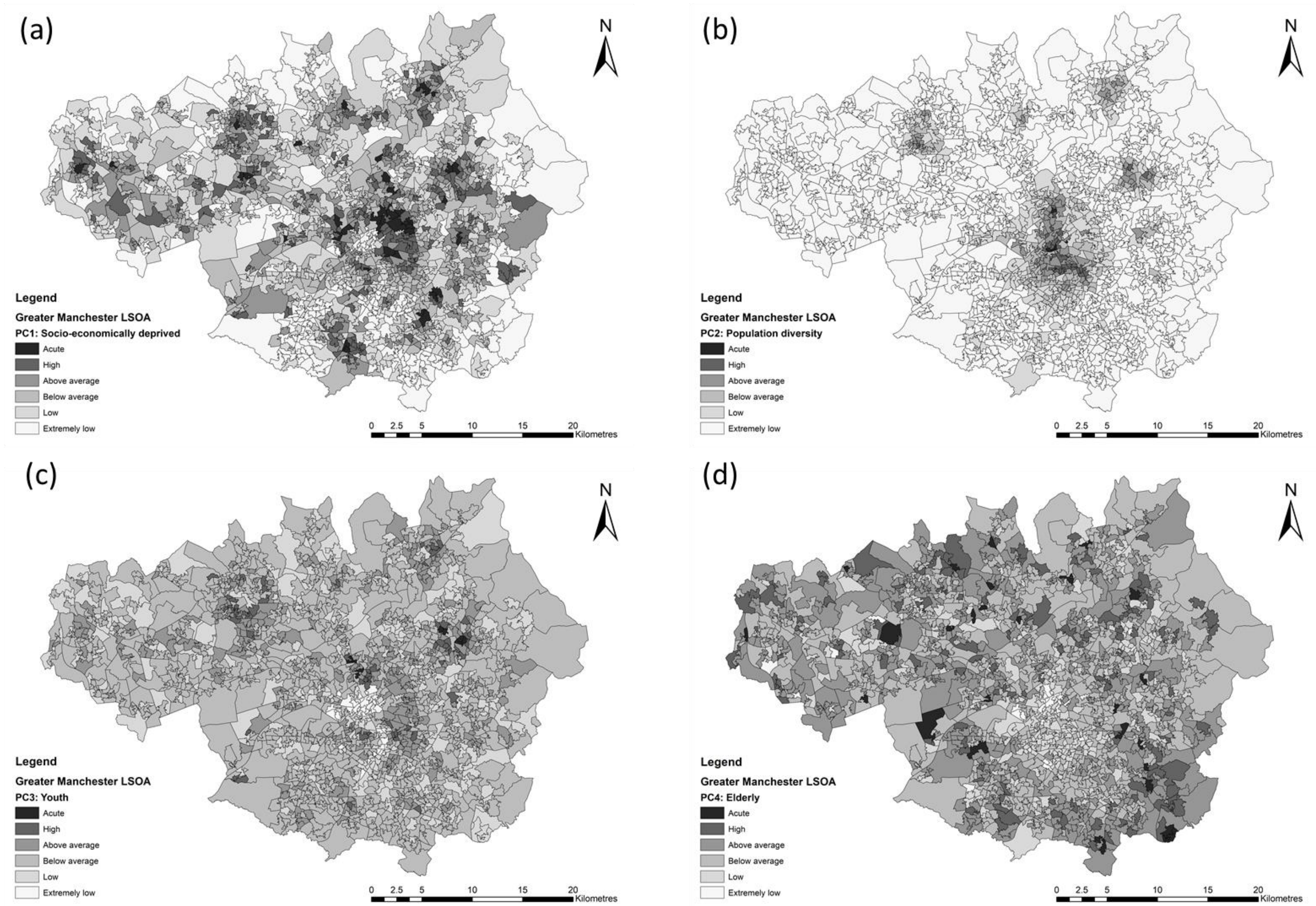

Figure 5.6: The four principal components of social vulnerability to environmental hazards in Greater Manchester at LSOA level (equal interval classification). (a) PC1 Socio-economically deprived, (b) PC2 Population diversity, (c) PC3 Youth, (d) PC4 Elderly. Base maps are © Crown Copyright/database right (2021). An Ordnance Survey/EDINA supplied service. Greater Manchester LSOA boundary data, ONS (2021).

The pattern displayed by the composite social vulnerability index for Greater Manchester (Fig. 5.7) emphasises that above average, high, and acute socially vulnerable neighbourhoods display an urban-related pattern of distribution, which is similar to the proportion of brownfield within LSOAs (Fig. 5.4). Higher social vulnerability is clustered around city and town centres in Greater Manchester, which reduces with distance from urban areas (Fig 5.7). There are relatively few areas displaying acute social vulnerability (1%, 16 LSOA) and 11% of LSOAs are identified as having high social vulnerability (Table 5.5). LSOAs displaying below average, low, and extremely low social vulnerability are more abundant than those above average levels (Table 5.5). Extending further towards the suburban and peri-urban boundaries, predominantly below average, low, and extremely low social vulnerability to environmental hazards is evident (Fig 5.7).

Table 5.5 Social vulnerability level distribution in Greater Manchester.

Level of social vulnerability	**Number of LSOA**	**% of LSOA**
Acute (0.84-1)	16	1.0
High (0.68-0.83)	184	11.0
Above average (0.51-0.67)	255	15.2
Below average (0.34-0.50)	344	20.6
Low (0.18-0.33)	494	29.5
Extremely low (0-0.17)	380	22.7

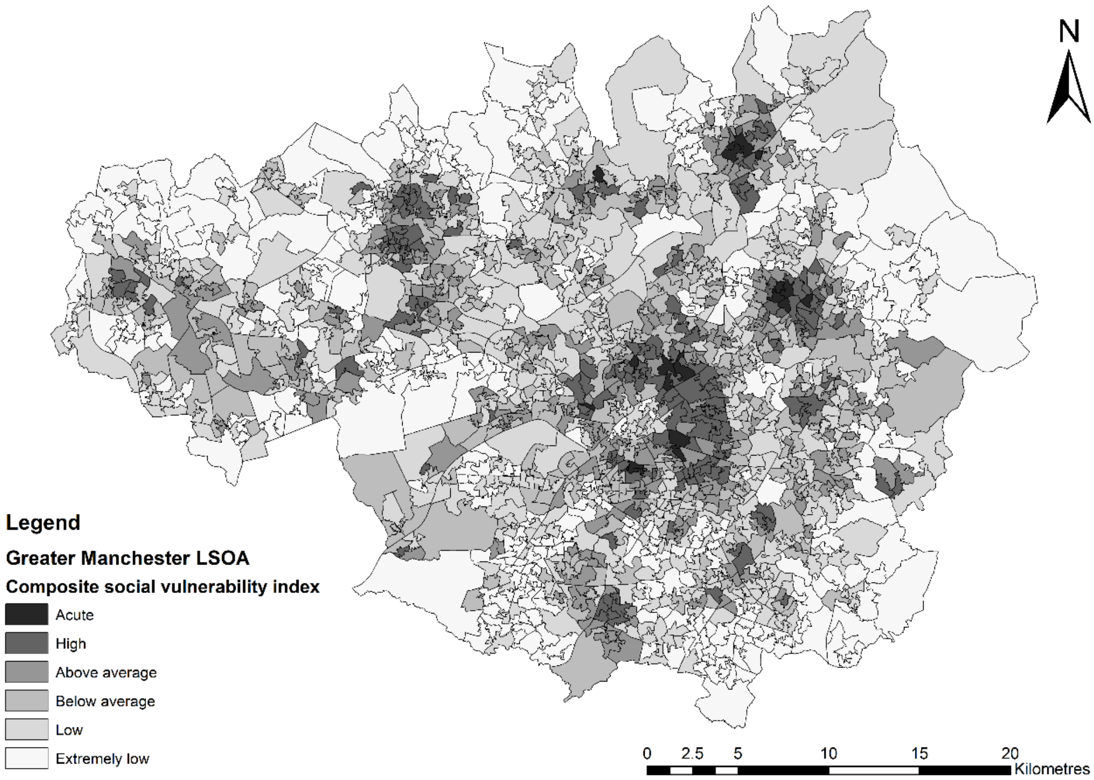

Figure 5.7: The spatial distribution of a composite index of social vulnerability in Greater Manchester. Base maps are © Crown Copyright/database right (2021). An Ordnance Survey/EDINA supplied service. Greater Manchester LSOA boundary data, ONS (2021).

5.3.2 Air quality

The spatial distribution of the modelled air pollutants across Greater Manchester (Fig. 5.8a) indicates that higher concentrations are prominent in the regional centre, generally decreasing toward the conurbation boundary in the north and east where peri-urban land cover is dominant (Fig 5.2). Compared to the distribution of social vulnerability (Figs. 5.7), lower air quality is centralised in the conurbation and encompasses significant areas identified with above average social vulnerability. Pockets of higher concentrations of air pollutants are evident around some urban centres. High concentrations of PM_{10} are widely distributed (Fig. 5.8b), with a reduction out towards the district centres, SO_2 displays higher concentrations in a wide centralised band which extends towards the south-west (Figure 5.8c). Figure 5.8d shows modelled estimates for NO_2 which is centralised regionally.

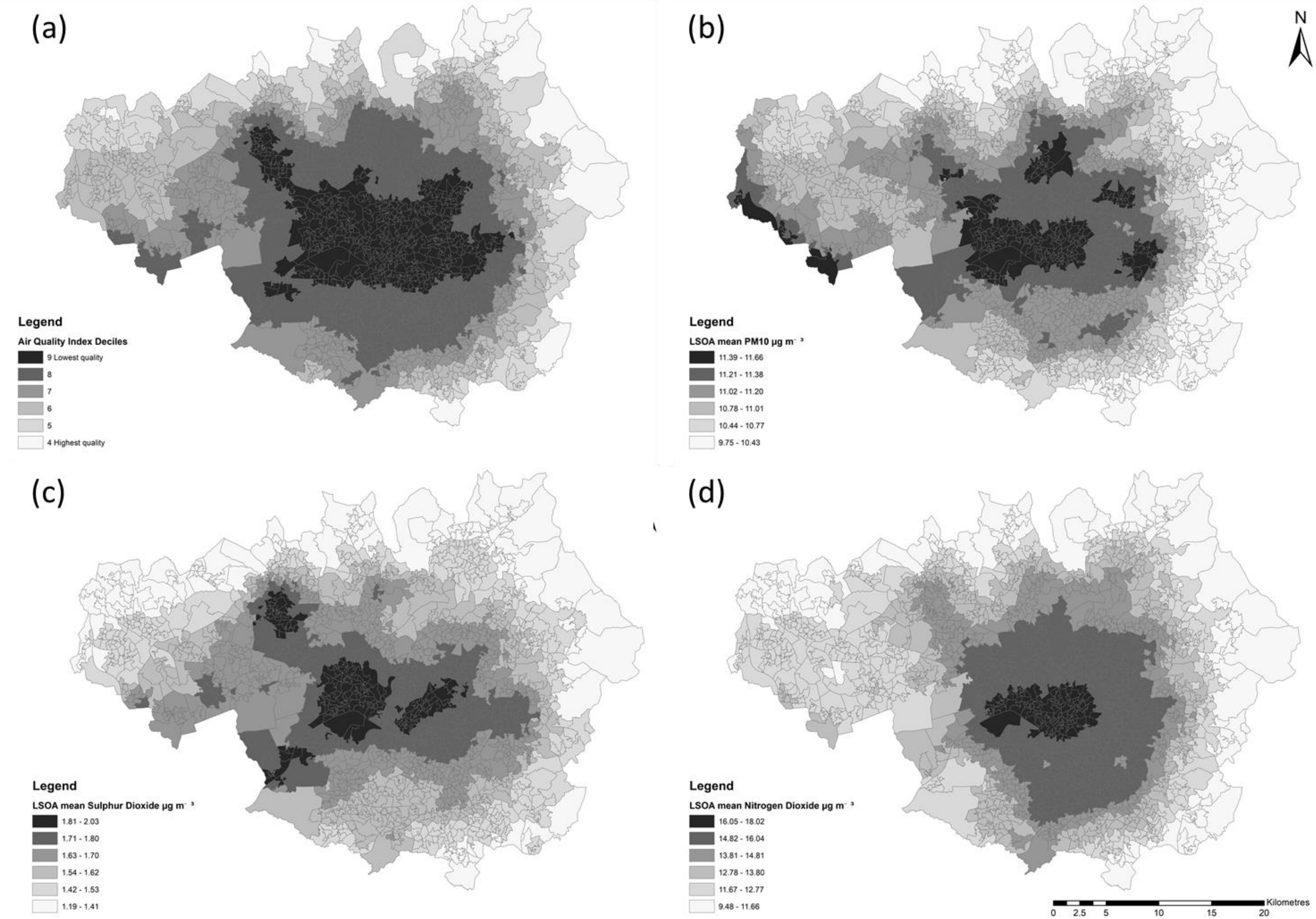

Figure 5.8: Modelled air pollutants, and air quality index deciles for Greater Manchester. (a) Air quality index deciles, (b) PM10, (c) SO2, (d) NO2. Base maps are © Crown Copyright/database right (2021). An Ordnance Survey/EDINA supplied service. Greater Manchester LSOA boundary data, ONS (2021), AHAH dataset (CDRC/University of Liverpool) (Consumer Data Research Centre, 2019) UK Open Government License (OGL).

5.3.3 Flooding

The spatial distribution of the flood hazard exposure across Greater Manchester (Fig. 5.9) indicates that the greatest risk of exposure is evident in the regional centre, and several urban and suburban areas. All Greater Manchester LSOA experience some degree of flood exposure, though most are affected in less than 5.5% of their total land area.

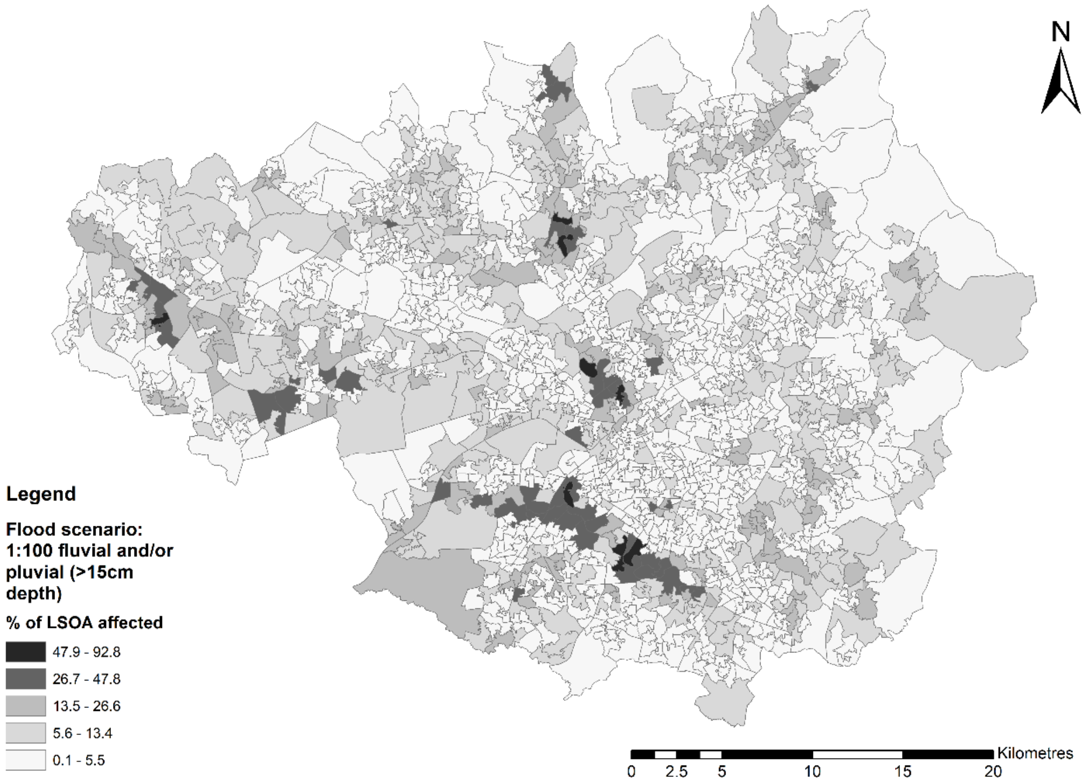

Figure 5.9: Fluvial and/or pluvial flood risk (% LSOA) map for Greater Manchester. Base maps are © Crown Copyright/database right (2021). An Ordnance Survey/EDINA supplied service. Greater Manchester LSOA boundary data, ONS (2021), Flood data: © Environment Agency copyright and/or database right 2021.

5.3.4 Spatial statistical relationships

Spatial autocorrelation analysis using univariate LISA reveals that each of the variables: brownfield proportion, social vulnerability (composite index and the component scores), flood exposure and air pollution exposure demonstrate significant spatial clustering (Moran's I values are greater than zero and significance <0.001) (Frazier, Thompson, Dezzani, & Butsick, 2013) (Fig. 5.10). Table 5.6 shows that High-High and Low-Low clusters, also referred to as hotspots and coldspots, occur for social vulnerability, air pollution, and flood exposure (in greater than 30% of LSOAs). In contrast, brownfield display less positive (16% High-High, Low-Low) clustering of LSOA. However, there are some visual similarities between cluster distribution of brownfield and flood exposure (Fig. 5.10). Coldspots for air pollution and social vulnerability also display some spatial similarities. All variables show hotspots centrally in the conurbation, indicating that areas with high brownfield proportion, social vulnerability and environmental hazard exposure coincide spatially (Fig. 5.10 & Table 5.6).

Analysing the components of social vulnerability using LISA further emphasises four main hotspots of socio-economically deprived (PC1), population diversity (PC2), and youth (PC3) in the central and northern district town or city centres (Fig. 5.11). The elderly (PC4) predominantly display hotspots clustered at the outskirts of the conurbation and coldspots in Greater Manchester's regional centre. Coldspots of socio-economically deprived (PC1) and population diversity (PC2) are evident in peri-urban regions. The component representing the youth (PC3) aspect of social vulnerability displays coldspots in the centre of the conurbation and isolated peri-urban areas.

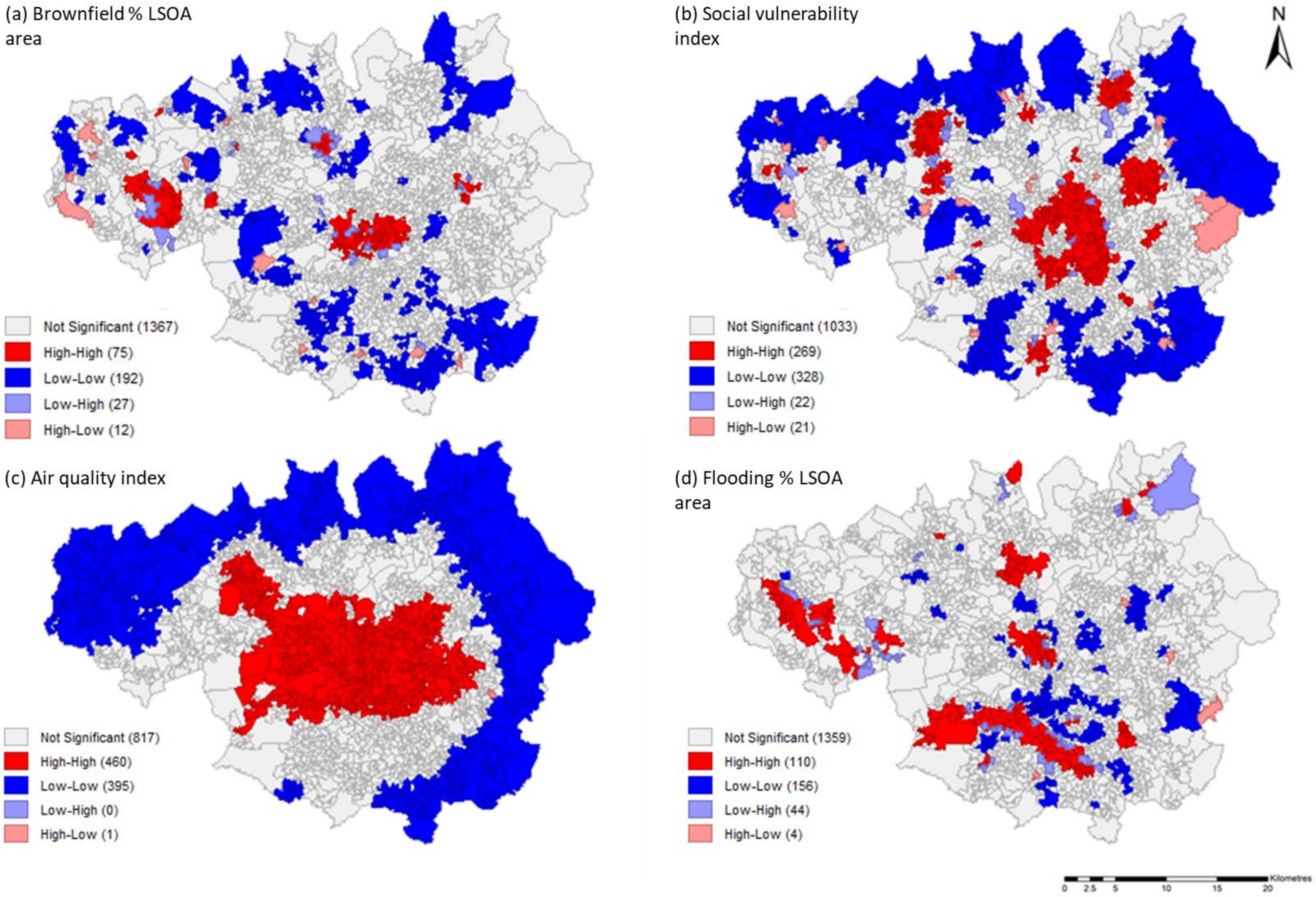

Figure 5.10: Local indicators of spatial autocorrelation cluster maps. (a) Brownfield, (b) Social vulnerability, (c) Air quality index, (d) Flooding.

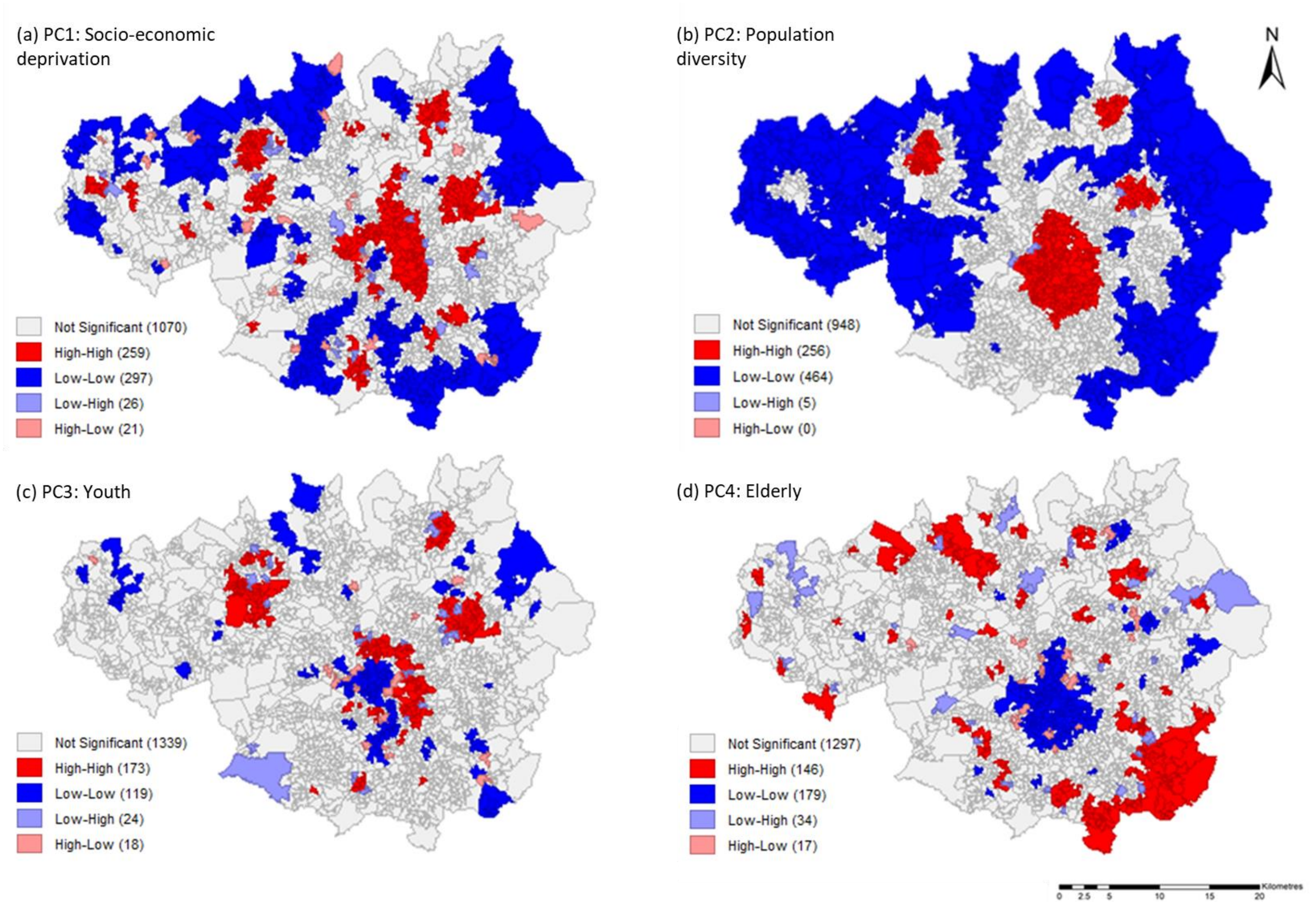

Figure 5.11: Local indicators of spatial autocorrelation cluster maps for components of social vulnerability. (a) PC1 Socio-economic deprivation, (b) PC2 Population diversity, (c) PC3 Youth, (d) PC4 Elderly.

Table 5.6: LISA Cluster significance statistics, and percentage and number of LSOA.

Variable	Cluster / Outlier	Number of LSOA	% of LSOA	Significance level	Number of LSOA
Brownfields	High-High	75	4.5	Local Moran's I	0.399
	Low-Low	192	11.5	p=0.001	35
	Low-High	27	1.6	p=0.01	68
	High-Low	12	0.7	p=0.05	203
	Not Significant	1367	81.7		
Social vulnerability index	High-High	269	16.1	Local Moran's I	0.58
	Low-Low	328	19.6	p=0.001	179
	Low-High	22	1.3	p=0.01	201
	High-Low	21	1.3	p=0.05	260
	Not Significant	1033	61.7		
PC1:	High-High	259	15.5	Local Moran's I	0.494
	Low-Low	297	17.8	p=0.001	121
	Low-High	26	1.6	p=0.01	201
	High-Low	21	1.3	p=0.05	281
	Not Significant	1070	64		
PC2:	High-High	256	15.3	Local Moran's I	0.822
	Low-Low	464	27.7	p=0.001	221
	Low-High	5	0.3	p=0.01	239
	High-Low	0	0	p=0.05	265
	Not Significant	948	56.7		
PC3:	High-High	173	10.3	Local Moran's I	0.462
	Low-Low	119	7.1	p=0.001	96
	Low-High	24	1.4	p=0.01	91
	High-Low	18	1.1	p=0.05	147
	Not Significant	1339	80		
PC4:	High-High	146	8.7	Local Moran's I	0.33
	Low-Low	179	10.7	p=0.001	66
	Low-High	34	2	p=0.01	131
	High-Low	17	1	p=0.05	179
	Not Significant	1297	77.5		
Air quality index	High-High	460	27.5	Local Moran's I	0.923
	Low-Low	395	23.6	p=0.001	322
	Low-High	0	0	p=0.01	304
	High-Low	1	0.1	p=0.05	230
	Not Significant	817	48.8		
Flood	High-High	110	6.6	Local Moran's I	0.368
	Low-Low	156	9.3	p=0.001	39
	Low-High	44	2.6	p=0.01	84
	High-Low	4	0.2	p=0.05	191
	Not Significant	1359	81.2		

Spatial autocorrelation using multivariate BiLISA reveals that multiple hotspots and coldspots exist between brownfield proportion and social vulnerability, flood exposure, and air pollution exposure (Fig 5.12 & Table 5.7). Results display Moran's I values greater than zero and significance values less than p=0.001, indicating significant spatial clustering (Fig 5.12 & Table 5.7) (Anselin, 2020; Frazier et al., 2013) (Fig 5.12 & Table 5.7). Hotspots occur between brownfield % and social vulnerability score (7.2% of LSOA), brownfield and air quality indicator deciles (9.6% of LSOA), and brownfield and flood exposure (2.9% of LSOA) (Fig 5.12 & Table 5.7). Social vulnerability displays hotspots with air quality deciles (17.2% LSOA) (Fig 5.13) and less so, flood exposure % (3.6% LSOA and Local Moran's I -0.044) (Fig 5.14). The results indicate greater spatial dependency between the hotspot and cold-spot cluster distribution of brownfield, social vulnerability, and air quality deciles (Fig 5.12 & Table 5.7). Similar hotspot clusters are also present for social vulnerability scores and air quality deciles (Fig 5.13). All BiLISA combinations of variables show hotspots centrally in the conurbation, indicating that there is a similarity in clusters between high brownfield proportion, social vulnerability, and environmental hazard exposure, which spatially overlap (Fig 5.12).

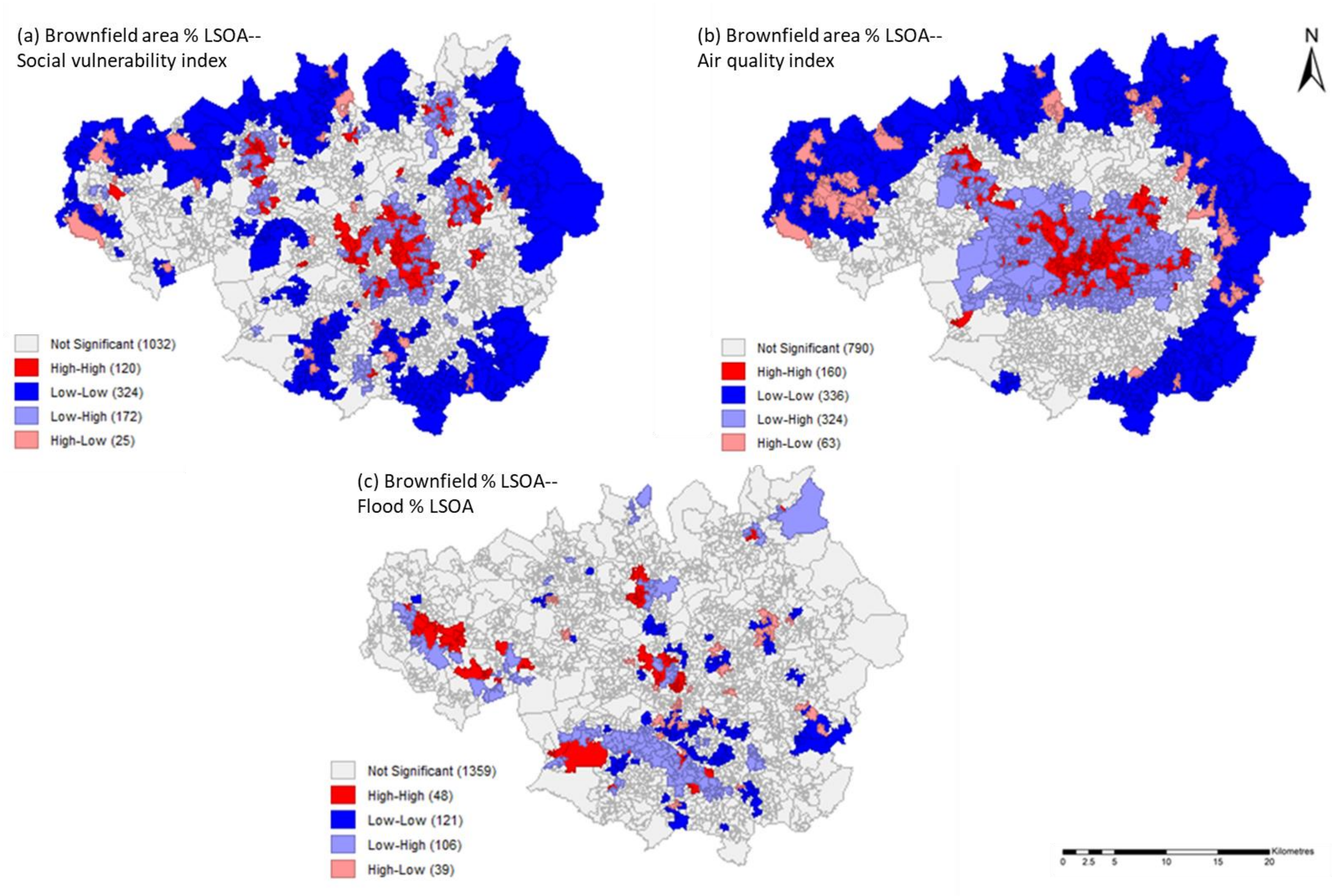

Figure 5.12: Bivariate local indicators of spatial autocorrelation cluster maps between brownfield, social vulnerability, and environmental hazards. (a) Brownfield--Socio-economic deprivation, (b) Brownfield—Air quality, (c) Brownfield—Flooding.

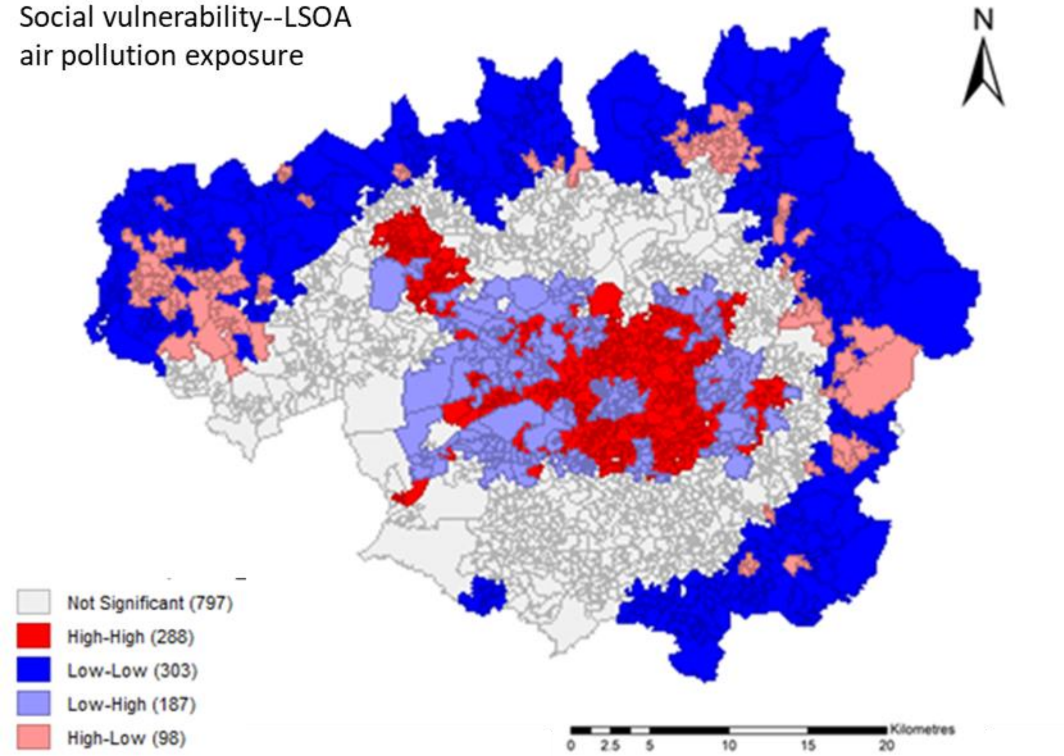

Figure 5.13: Bivariate local indicators of spatial autocorrelation cluster maps, social vulnerability and increased air pollution exposure.

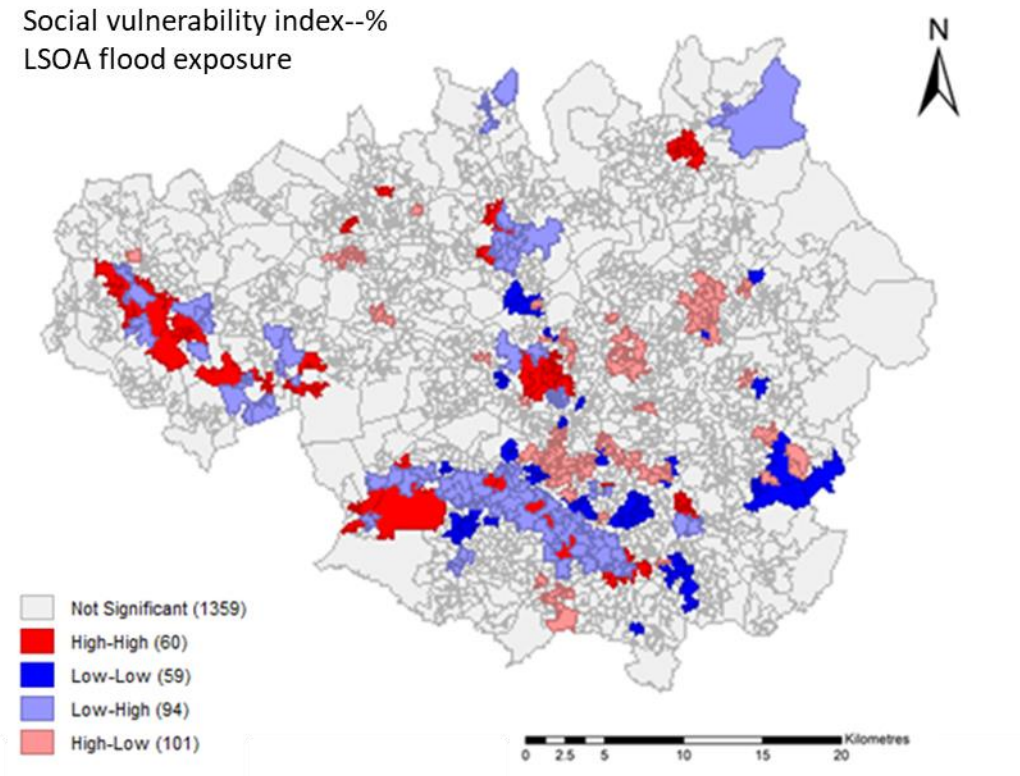

Figure 5.14: Bivariate local indicators of spatial autocorrelation cluster maps for social vulnerability and flooding.

Table 5.7: BiLISA cluster significance statistics, and percentage and number of LSOA.

First Variable (x axis)	Second Variable (y axis)	Cluster / Outlier	Number of LSOA	% of LSOA	Significance level	Number of LSOA
Brownfields	**Social vulnerability index**	High-High	120	7.2	Local Moran's I	0.163
		Low-Low	324	19.4	p=0.001	179
		Low-High	172	10.3	p=0.01	200
		High-Low	25	1.5	p=0.05	262
		Not Significant	1032	61.7	No significance	1032
Brownfields	**Air Quality Index**	High-High	160	9.6	Local Moran's I	0.13
		Low-Low	336	20.1	p=0.001	413
		Low-High	324	19.4	p=0.01	255
		High-Low	63	3.8	p=0.05	215
		Not Significant	790	47.2	No significance	790
Brownfields	**Flooding**	High-High	48	2.9	Local Moran's I	0.034
		Low-Low	121	7.2	p=0.001	39
		Low-High	106	6.3	p=0.01	84
		High-Low	39	2.3	p=0.05	191
		Not Significant	1359	81.2	No significance	1359
Social vulnerability index	**Air pollution**	High-High	288	17.2	Local Moran's I	0.351
		Low-Low	303	18.1	p=0.001	377
		Low-High	187	11.2	p=0.01	286
		High-Low	98	5.9	p=0.05	213
		Not Significant	797	47.6	No significance	797
Social vulnerability index	**Flooding**	High-High	60	3.6	Local Moran's I	-0.044
		Low-Low	59	3.5	p=0.001	39
		Low-High	94	5.6	p=0.01	84
		High-Low	101	6	p=0.05	191
		Not Significant	1359	81.2	No significance	1359

5.3.5 Statistical relationships between brownfield, social vulnerability, and environmental hazards

Analysis of the equal interval social vulnerability classes and brownfield area % within each level of social vulnerability (Figs. 5.15 & 5.16) reveals a very strong positive correlation (R^2= 0.982) emphasising the disproportionate distribution of brownfield sites in socially vulnerable neighbourhoods (LSOAs). Areas with acute social vulnerability have 8 times more brownfield land area than areas with extremely low social vulnerability.

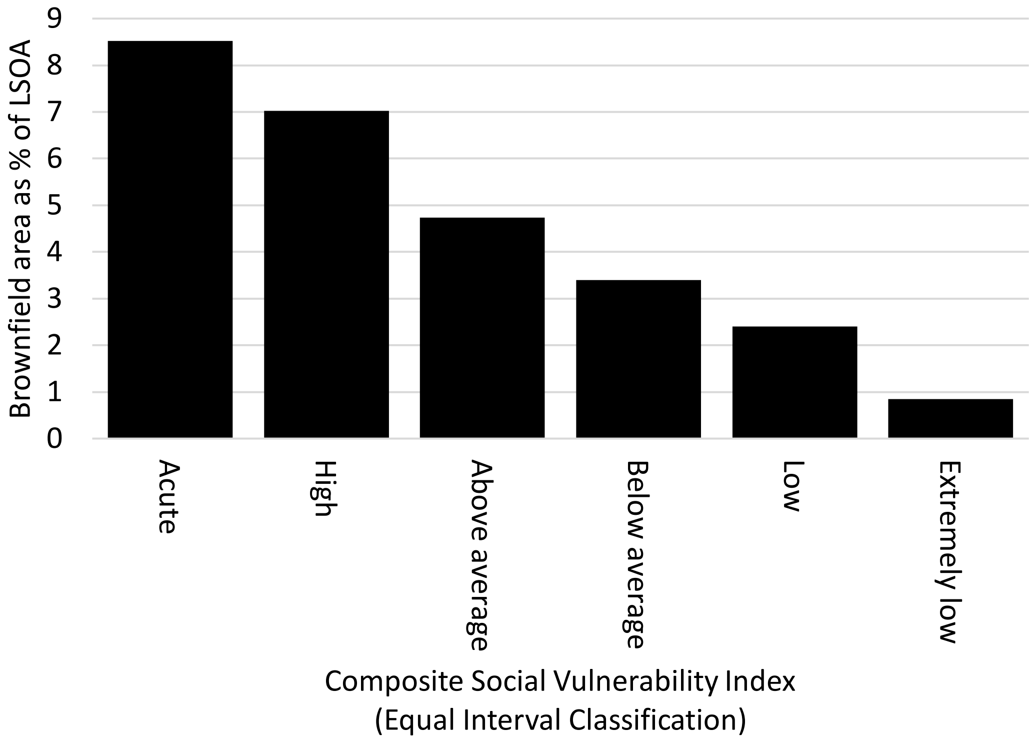

Figure 5.15: The mean brownfield area as a % of LSOA within areas exhibiting each equal interval level of the composite social vulnerability index.

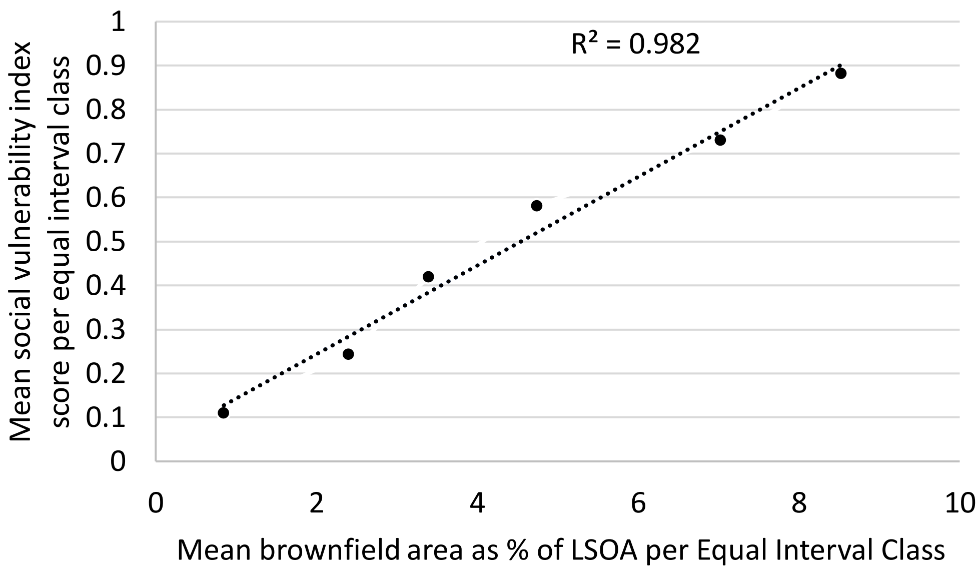

Figure 5.16: Linear regression analysis of the mean composite social vulnerability index score and mean brownfield area per equal interval class (R^2=0.982).

Examining the associations between social vulnerability, brownfield and environmental hazards reveals that increases in the composite social vulnerability index score, socio-economic deprivation (PC1), population diversity (PC2), and youth (PC3) are negatively associated with increased risk of flood exposure (Table 5.8). The spatial distribution of LSOAs displaying higher levels of social vulnerability (composite index), socio-economic deprivation

(PC1), population diversity (PC2) and youth (PC3) are positively correlated with areas exhibiting low air quality and increased air pollution (Table 5.8). The neighbourhoods characterised by high proportion of the elderly (PC4) are negatively correlated with air pollution (Table 5.8). Only the youth component (PC3) is not positively or negatively correlated with brownfield.

Table 5.8: Spearman's rank correlations between social vulnerability and environmental hazards.

Social vulnerability dimensions and composite index	% LSOA affected by Flood	Air quality index deciles	Brownfield % of LSOA
Composite social vulnerability index	-.111**	.342**	.319**
PC1: Socio-economic deprivation	-.068**	.231**	.298**
PC2: Population diversity	-.190**	.617**	.256**
PC3: Youth	-.087**	.063*	0.046
PC4: Elderly	0.013	-.299**	-.175**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 5.9 shows results of the Spearman's rank correlations between the brownfield typology, social vulnerability, and environmental hazards. This reveals that the composite social vulnerability index and communities characterised by high socio-economic deprivation (PC1), high population diversity (PC2), and youth (PC3), positively coincide with an increased area of several brownfield types. The elderly (PC4) are inversely related to the proportion of brownfield present in associated LSOAs (Table 5.9). Increasing composite social vulnerability index scores, socio-economic deprivation (PC1), and population diversity (PC2) are positively correlated with increased proportions of numerous types of brownfields, exhibiting a wide range of ecosystem service provision. However, youth (PC3), is only positively associated with four brownfield types providing moderate ecosystem services, and moderate to high perviousness (BESI 4-7, BPI 5-10 in Table 5.9), and negatively associated with several brownfields providing low ecosystem services (BESI 1-3) (Table 5.9). The elderly (PC4) display either no significant associations or is negatively correlated with several brownfield types. Only the composite social vulnerability index and the socio-economically deprived (PC1) display positive associations with brownfields that provide the highest levels of brownfield ecosystem service provision (BESI 8-10) (Table 5.9).

Examining Spearman's rank correlation between brownfields and environmental hazards reveals numerous positive correlations where increased proportion of brownfield types and increased exposure to environmental hazards coincide spatially (Table 5.9). Thus, neighbourhoods at increased risk of flooding and lower air quality contain more brownfield land. Many positive correlations occur between brownfield types with low ecosystem service provision (BESI 1-3), low perviousness (BPI) and areas with increased risk of environmental hazard exposure (Table 5.9). Three brownfield types with high ecosystem service provision and perviousness (BESI 8-10, BPI 7-9) are positively correlated with increased flood exposure, and areas of increased air pollution, which are, highly vegetated supplementary or enclosed, densely vegetated, irregular shape and vegetated (Table 5.9).

Table 5.9 provides recommendations for planning and practice for each brownfield type based upon the associations with vulnerability and hazards. These are suggestions that may enhance or maintain urban resilience based on their perviousness (BPI) and ecosystem service provision (BESI) and include:

- Strategic greening opportunities
- The break-up of impervious surfaces
- The opening up of sites for public use
- The avoidance of redevelopment

Three types of brownfield display a positive correlation with increased social vulnerability and environmental hazards, which exhibit high ecosystem service provision, and perviousness – irregular shape and vegetated, highly vegetated supplementary or enclosed, and scrub grassland. To maintain or increase urban resilience it is recommended that these three types of brownfield remain undeveloped and public access provided. Increased extent of two types of brownfield – impervious grey surfaces, and functional and civic grey space, coincide spatially with increased social vulnerability, flooding, and air pollution, though provide minimal ecosystem service provision or pervious ground. It is recommended that these two types of brownfield undergo strategic greening and the breaking up of impervious surface materials.

Vegetated with water body, and utilities, mill ponds and lodges brownfield types are highly pervious and provide beneficial ecosystem services but are not spatially associated with social vulnerability or environmental hazards. It is recommended that these two types of brownfield could still improve urban resilience by ensuring open public access and remain undeveloped. The densely vegetated brownfield types correlates positively with increased social vulnerability and either increased flood risk or low air quality, which delivers high ecosystem service provision and pervious land. It is therefore recommended that densely vegetated brownfields are left undeveloped and open access. Brownfield types, Buildings and compact commercial units are the least pervious and the least beneficial for ecosystem services, positively correlated with increased social vulnerability, flooding, or air pollution. It is recommended that these brownfield types have their impervious surfaces broken up to improve perviousness and allow natural succession to take hold.

Table 5.9: Spearman's rank correlations between the brownfield typology, social vulnerability, and environmental hazards. This table indicates where an increase in area of a brownfield type positively correlates with increases in social vulnerability and the risk of increased exposure to flooding and air pollution. Recommendations for planning policy / practice are made for each brownfield type to maintain or enhance urban resilience.

Brownfield typology % of LSOA	Brownfield Ecosystem service Index (BESI)	Brownfield Perviousness Index (BPI)	PC1: Socio-economic deprivation	PC2: Population diversity	PC3: Youth	PC4: Elderly	Social vulnerability index	% LSOA affected by Flood	Air quality index deciles	Suggestions to maintain or enhance urban resilience
All Brownfield	N/A		.298**	.256**	0.046	-.175**	.319**	.116**	.194**	
(a) Buildings	1	1	0.035	.192**	-.151**	-.089**	.070**	0.04	.123**	Break-up impervious surfaces
(b) Compact commercial units	1	2	.054*	.125**	-.090**	-0.034	.068**	0.035	.065**	Break-up impervious surfaces
(l) Hard surface with disturbed ground	1	5	0.037	.119**	-0.013	-.097**	.068**	0.012	.071**	Strategic greening opportunities; Break-up impervious surfaces
(c) Impervious grey surfaces	2	1	.088**	.209**	-.058*	-.144**	.125**	.079**	.122**	Strategic greening opportunities; Break-up impervious surfaces
(d) Industrial units with yards	2	1	.098**	.193**	-.085**	-.103**	.127**	-0.002	.167**	Strategic greening opportunities; Break-up impervious surfaces
(e) Functional and civic grey space	2	2	.105**	.152**	-0.04	-.095**	.117**	.076**	.135**	Strategic greening opportunities; Break-up impervious surfaces
(j) Large industrial with peripheral vegetation	3	4	0.044	0.026	0.045	-.059*	0.044	.099**	0.002	Strategic greening opportunities; Break-up impervious surfaces
(s) Urban pioneer vegetation and amenity grassland	3	7	.145**	0.035	-0.001	-0.019	.131**	0.03	0.034	Strategic greening opportunities
(f) Large Dilapidated Industrial or Commercial	4	2	.098**	.111**	-0.02	-0.044	.109**	0.001	.108**	Strategic greening opportunities; Break-up impervious surfaces
(k) Built with managed or pioneer vegetation	4	4	.091**	0.042	0.013	-0.039	.087**	0.026	0.032	Strategic greening opportunities; Break-up impervious surfaces
(u) Informal open grassland	4	10	.135**	.064**	.075**	-0.037	.134**	0.012	.054*	Strategic greening opportunities
(i) Hard surfaced with peripheral vegetation	5	4	.058*	.096**	-.055*	-.089**	.072**	.055*	0.018	Strategic greening opportunities; Break-up impervious surfaces
(q) Disturbed and vegetated	5	7	.113**	.122**	0.007	-.083**	.128**	.051*	.092**	Strategic greening opportunities
(g) Built with water body	6	3	.051*	0.047	-0.024	-0.014	.052*	.057*	0.004	Strategic greening opportunities; Break-up impervious surfaces
(n) Site remnants and foundations with successional vegetation	6	6	.190**	.073**	.064**	-0.015	.175**	-0.01	0.047	Strategic greening opportunities
(t) Scrub grassland	6	9	.160**	.062*	.073**	-0.046	.149**	.059*	.097**	Strategic greening opportunities; Open up for public use; Avoid redevelopment
(h) Industrial with peripheral vegetation	7	3	.064**	.089**	-.077**	-0.028	.070**	0.042	.071**	Break-up impervious surfaces
(m) Properties with mud-successional vegetation or remnant gardens	7	5	.066**	0.008	.061*	-0.02	.061*	0.042	0.033	Break-up impervious surfaces
(z) Very large open green space	7	10	0.047	-.094**	0.023	-0.009	0.027	.098**	-.075**	Open up for public use; Avoid redevelopment
(v) Large open vegetated	8	8	0.029	-.079**	-0.012	-0.01	0.005	.131**	-0.024	Open up for public use; Avoid redevelopment
(w) Utilities, mill ponds and lodges	8	9	0.01	-0.011	-0.01	0.021	0.001	0.036	-0.014	Open up for public use; Avoid redevelopment
(o) Uneven and vegetated	9	6	-0.046	-0.036	-0.04	-0.004	-.053*	.067**	-.066**	Open up for public use; Avoid redevelopment
(x) Highly vegetated supplementary or enclosed	9	7	.136**	0.039	0.026	-0.03	.126**	.114**	.052*	Open up for public use; Avoid redevelopment
(y) Densely vegetated	9	9	.076**	-0.032	0.01	-0.011	.055*	.096**	0.045	Open up for public use; Avoid redevelopment
(r) Vegetated with water body	10	6	-0.038	-0.044	-0.001	0.007	-0.043	0.043	-0.04	Open up for public use; Avoid redevelopment
(p) Irregular shape and vegetated	10	8	.104**	0.029	0.005	-0.014	.090**	.054*	.087**	Open up for public use; Avoid redevelopment

** Correlation is significant at the 0.01 level

* Correlation is significant at the 0.05 level

	An increase in area of this type of brownfield is positively correlated with an increase in social vulnerability and risk of flooding and air pollution
	An increase in area of this type of brownfield is positively correlated with an increase in social vulnerability and risk of either flooding or air pollution
	An increase in area of this type of brownfield is positively correlated with either increased social vulnerability or increased flood risk
	No correlation with an increase in social vulnerability or environmental hazards
	Strategic greening opportunities
	Break-up impervious surfaces
	Open up for public use
	Avoid redevelopment

5.4 Discussion

The social vulnerability index displays the spatial distribution of neighbourhood vulnerability to environmental hazards in Greater Manchester. The spatial patterns suggest that the most at-risk communities reside in many town and city centres within the urban and suburban conurbation. This division is well represented when examining the separate dimensions of vulnerability. Areas with higher-than-average socio-economic deprivation (PC1), and population diversity (PC2), which explained the highest proportion of variance in the data, tend to occur close to town centres and their immediate suburbs. This is indicative of common patterns of urban deprivation in UK towns and cities and globally (Townsend, 1987; Wratten, 1995), and mirrors previous geographies of diversity in Greater Manchester (Jivraj, 2013). The least vulnerable communities reside primarily in peri-urban and suburban areas. However, the aspects of vulnerability represented by Youth (PC3), are distinctly suburban, and the elderly (PC4), mostly peri-urban, and thus represent a proportion of Greater Manchester's population that are vulnerable to environmental hazards who are not urban centric. The results of this analysis updates work undertaken by Kaźmierczak and Cavan (2011) in Greater Manchester, and identity very similar principal components of social vulnerability and little change in the spatial distribution of social vulnerability components in the interceding decade. This may suggest that vulnerability is a longstanding issue that takes a long time to address.

LISA and BiLISA analysis identified multiple hotspots of brownfield, social vulnerability, air pollution, and flooding which suggest broadly urban trends. All variables display significant hotspots in the centre of the conurbation and identify intersections in their spatial patterns. This emphasises the potential of brownfield in these areas to provide solutions in socially vulnerable neighbourhoods to lessen exposure to flooding and air pollution. Brownfield and flooding hotspots also display clusters to the west of the conurbation where several very large open vegetated brownfields have been identified (see **Chapter 3**), potentially useful for promoting flood water drainage in these areas (or which may exasperate flood exposure if developed) (Uzomah et al., 2014). Hotspots of low air quality display the most significant distribution in the LISA maps and spatially coincide with many hotspots of brownfield and social vulnerability in the BiLISA maps.

Visual interpretation of the socio-economically deprived (PC1), population diversity (PC2), and youth (PC3) LISA maps suggest multiple intersections with low air quality. The risks of air pollution to these demographics of population are well documented in the literature (Brunt et al., 2017; Cole & Neumayer, 2004; Schwela, 2000; Sunyer et al., 2015). Installation of green infrastructure to ameliorate adverse health effects has been documented as an appropriate intervention (Abhijith et al., 2017; Grote et al., 2016; Nowak et al., 2006; Selmi et al., 2016; Vos, Maiheu, Vankerkom, & Janssen, 2013), and brownfield has the potential space to provide this. Brownfields also display multiple hotspots where clusters of the socio-economically deprived (PC1), ethnically diverse (PC2) communities, and increased environmental hazard exposure exist. These aspects of social vulnerability have been linked to a lack of access to urban green space (Mitchell & Popham, 2007; Sister et al., 2010). This indicates that brownfields may have significant potential to provide additional green space provision in these areas.

There is a significant linear relationship between increasing social vulnerability and brownfield extent in Greater Manchester, with acute socially vulnerable areas containing, on average, eight times more brownfield land cover than those with very low vulnerability. This is likely due to the similar spatial distribution of the socio-economically deprived (PC1) and population diversity (PC2) components, which are most clustered in densely built up urban areas (Hall, 2006; Kaźmierczak & Cavan, 2011), as are brownfields (Oliver et al., 2005).

Examining Spearman's rank correlation between brownfields, social vulnerability and environmental hazard exposure revealed that LSOAs with increased social vulnerability and environmental hazard exposure, exhibited an increased proportion of many individual brownfield types. Introducing environmental performance indicators (BESI and BPI) to the brownfield typology revealed the socio-ecological value of each type of brownfield. Based on this, four key recommendations for brownfield were made, including:

- Strategic greening opportunities
- The break-up of impervious surfaces
- The opening up of sites for public use
- The avoidance of redevelopment

The most valuable brownfield types (providing the greatest environmental benefits) and positively spatially correlated with increased social vulnerability, and exposure to low air quality and flood risk include: Irregular shape and vegetated; highly vegetated supplementary or enclosed; and, scrub grassland. For these three brownfield types, redevelopment should be avoided, and managed to enable public access. Brownfield types, impervious grey surfaces, and functional and civic grey spaces were identified as having the most potential to aid urban resilience if impervious surface are disaggregated and strategically greened.

The abundance of brownfield, with both high and low ecosystem service provision, in socially vulnerable neighbourhoods, (and the disparities between urban brownfield and parks, see **Chapter 4**), suggest that brownfield could provide additional open green space. The creation of new open green space on brownfield in urban areas could increase social equity by improving environmental conditions in urban areas (Rall & Haase, 2011; Wolch et al., 2014). 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). Minor modifications to vegetated brownfield identified in socially vulnerable areas could increase the provision of accessible green space whilst retaining most ecosystem services (Mathey et al., 2015). In some cases, simply removing barriers to provide access will entice the public to use the site for recreational activities (Kamvasinou, 2017).

Three types of brownfield exhibiting high ecosystem service provision (BESI 9-10) are positively correlated with the composite social vulnerability index. These include highly vegetated supplementary or enclosed, densely vegetated, irregularly shaped and vegetated brownfield which have likely been vacant and providing several urban ecosystem services for an extended period of time (Robinson & Lundholm, 2012; Schadek et al., 2009). These highly beneficial brownfields should remain undeveloped to avoid negative ecosystem service impacts to areas already vulnerable to environmental hazards. Furthermore, these sites should be the focus of environmental improvements and perhaps opening up access to users as in many cases physical barriers prevent access to the public (Kamvasinou, 2011).

Many brownfield sites spatially corresponding with the composite social vulnerability index scores are revealed to exhibit low or moderate ecosystem services (BESI 1-7), and perviousness (BPI 1-7), with the exception of informal open grassland, which are highly pervious, but provide relatively low ecosystem service provision. The transformation of these brownfields into new green space, has the potential to deliver significant benefits to human health and well-being whilst addressing environmental injustice (Mathey et al., 2015). Furthermore, conversion of pervious brownfields for biomass production has been shown to be capable of significant fuel production for local areas, capable of alleviating economic deprivation and providing multiple ecosystem services (Donaldson & Lord, 2018; Lord, Atkinson, Lane, Scurlock, & Street, 2008).

Other notable opportunities identified include the prominence the young (PC3) in suburban areas where brownfield types displaying moderate ecosystem service provision (BESI 4-7), and containing some highly pervious land cover (BPI 5-10) are positively correlated. Goodchild and

Cole (2001) acknowledge higher densities of the young in suburban social housing estates, which here are associated with informal open grassland, site remnants with successional vegetation, scrub grassland, and properties with mid successional vegetation or remnant gardens (Table 5.9). However, no associations are recorded for PC3 and brownfields with high BESI, but positive correlations with low air quality are observed. This suggests that strategic greening and tree planting on these sites may provide resilience against poor air quality, reducing potential health risks of air pollution to young people (Flouri, Midouhas, & Joshi, 2014; Sunyer et al., 2015).

The findings suggest a substantial capacity for brownfields (in view of their location, quantity, and extent) to provide ecosystem services in areas with increased social vulnerability to environmental hazards. The air pollution removal benefits of individual brownfield were identified in **Chapter 4**, and represented by the BESI here, emphasises the importance of high performance brownfield sites which correspond spatially with high social vulnerability and poor air quality (Anderson & Minor, 2017). Redevelopment of these sites could see negative ecosystem service impacts (Robinson & Lundholm, 2012) for highly vulnerable communities.

The ecosystem service benefits provided by trees and vegetation in urban areas (including air pollution removal and flood attenuation) are well recognised (Beckett, Freer-Smith, & Taylor, 1998; Bolund & Hunhammar, 1999; Elmqvist et al., 2016; Robinson & Lundholm, 2012), especially for socially vulnerable communities (Dobbs, Martinez-Harmz, & Kendal, 2017; Meerow & Newell, 2017). The links found between brownfield and reduced air quality in highly vulnerable communities advocate capitalising on these existing sites by maintaining their valuable and productive ecosystem services and refraining from redevelopment, whilst transforming and/or redeveloping existing impervious brownfields (Mehdipour & Nia, 2013).

The relationship identified between brownfield types with low ecosystem service provision, e.g. impervious grey spaces and LSOA with higher flood risk exposure, stresses the potential of these brownfields to attenuate flood events if sufficient modifications are undertaken (Carroll & Kanarek, 2018). Song et al. (2019) has recommended several nature-based solutions for brownfield including constructing wetland, phytoremediation, for the type of sites identified here, which can provide environmental, ecological, and economic benefits whilst reducing flood risk. However green solutions to help mitigate urban flooding is not currently widely incorporated into urban flood management strategies, with some barriers cited as lack of open space for installation (Dhakal & Chevalier, 2017), which is disputed by findings here.

Brownfield land, with the installation of green or engineered drainage solutions (SUDS), could aid resilience of urban areas to flooding, reducing exposure and risk of the socially vulnerable to flood events (Song et al., 2019). Areas where flood exposure and highly pervious brownfields (e.g. large open vegetated, and very large open green space), or those providing high levels of ecosystem services (e.g. highly vegetated supplementary or enclosed and densely vegetated) correspond spatially, are likely already playing a role in urban resilience. Should these types of brownfields be redeveloped with impervious construction materials, then flood water will be displaced changing urban flood exposure dynamics (Oke, 2002).

5.5 Limitations

Data quality and accuracy are an important aspect geospatial and statistical analysis and can have a substantial impact on outputs (Veregin, 1999). Both flood and air pollution datasets represent modelled indicators and not specific data and other areas not represented here may be at risk from other hazard sources or events (Consumer Data Research Centre, 2019; Environment Agency, 2020a, 2020b). This was addressed by sourcing robust data from reputable sources (Consumer Data Research Centre, 2019; Environment Agency, 2020a, 2020b). The social vulnerability research undertaken gave a broad overview of social vulnerability in the study area, however commonly used indicators were selected from available data and further indicators may represent social vulnerability which were not utilised here. There was an issue of ecological fallacy regarding the scale at which social vulnerability and environmental hazard risk were analysed (LSOA) and data was not indicative or representative of all people or communities that reside within them.

Chapter 6: Conclusion

6.1 Introduction and chapter outline

The principal aim of this research was **to explore how brownfield ecosystem services may contribute to building resilience to environmental hazards in urban areas**. To achieve this aim three research objectives were completed. **Sections 6.2-6.4** reiterate each objective, presenting the key findings, and highlighting the contribution to knowledge. **Section 6.5** presents a research critique and explores further lines of enquiry. Finally, implications for policy and practice are discussed in **Section 6.6**.

6.2 Objective 1: Summary and contributions to knowledge

Objective 1: To characterise brownfield land, including consideration of spatial land use and land cover characteristics, and distribution across the urban environment (**Chapter 3**).

- An up-to-date database revealed a significant number (2197) and area (3163ha) of brownfield sites in Greater Manchester.
- A novel brownfield typology was developed using k-means clustering, with land cover, size, shape, and topography as criteria. This identified twenty-six distinct types of brownfield that vary in terms of vegetation type/succession, impervious and pervious land cover, and also distinguishes large, topographically challenging, and irregularly shaped sites.
- The brownfield typology displays distinct spatial patterns across the urban setting.
- Brownfields, overall, are more than 50% vegetated (51.25%) and highly pervious (58.72%) urban spaces.
- Brownfield with physical limitations to redevelopment are the most highly vegetated.

A review of the literature identified significant gaps in brownfield research. Most notably, a lack of assessment of the extent and distribution of brownfield at a city scale, and the absence of a readily transferable brownfield classification system that would enable consideration of both development potential and socio-ecological context. To address these gaps, an up-to-date geospatial database of Greater Manchester brownfield was created, a novel brownfield typology was developed based on landscape metrics (size, shape, and slope) in combination with land cover characterisation, and the typology was then mapped across the urban matrix.

The findings provided a comprehensive characterisation of the structure, patterns, distribution, and relationships between multiple brownfield types. The brownfield typology demonstrated the diversity of these brownfields and emphasised the transitional nature of brownfields after abandonment. These results illustrate that urban brownfield are dynamic spaces and potentially a valuable contributor to a city's green infrastructure and ecosystem services. Many of the brownfield types identified also have scope to be managed to increase their benefits to enhance urban resilience. This approach provides a useful insight into the socio-ecological characteristics of brownfield in urban areas, important for urban resilience and sustainable urban planning.

This research provides several **contributions to knowledge**. **First**, a widely transferable methodological approach to develop a brownfield typology. The use of attributes present in any urban plot make it widely applicable to post-industrial cities and for a wide range of urban land uses (as observed in the development of the urban park typology in **Chapter 4**). **Second**, it provides a case study that applies the approach, mapping brownfield at the city scale, which demonstrates the importance of considering the diversity of brownfield in assessment. **Third**, it quantifies the character of brownfield to understand ecological characteristics across the city which provides further information about brownfield conditions. This provides an immediate indication of niche ecological, and ecosystem service provisioning in these areas (Robinson & Lundholm, 2012), and across the city as a whole, where the baseline datasets can be further analysed to gain greater insight into current and potential ecosystem service provision**.**

6.3 Objective 2: Summary and contributions to knowledge

Objective 2: To assess the current provision of regulating ecosystem services of brownfield land, the potential if greened, and compare to existing urban green infrastructure (**Chapter 4**).

- Brownfields are estimated to provide approximately five times more regulating ecosystem services than parks in densely built urban areas, due to the disproportionate area of vegetated brownfield compared to parks.
- Brownfields have considerable potential to further benefit urban (a 797% increase) and sub-urban (367% increase) ecosystem service provision, with some intervention.
- The structure and composition of tree species on disturbed brownfield land, are shown to be key to the contribution of ecosystem services by brownfield.

- The typology methodology was applied to urban parks, identifying twelve types of park land.
- Parks were estimated to provide three times more regulating ecosystem services than brownfield overall.
- Several specific types of brownfield, including: Irregular shaped and vegetated; densely vegetated; vegetated with water body; and, uneven and vegetated, provide more regulating ecosystem services per unit area than all but three types of park.
- The methods developed in **Chapters 3 and 4** are highly transferable and could be applied to other urban land uses and to other post-industrial cities for ecosystem services research.

There is a paucity of evidence in the existing literature considering regulating ecosystem services provision by brownfields. In particular, how this contributes to existing urban green infrastructure and ecosystem services, and how these benefits are distributed across urban areas. To address these gaps, **Chapter 4** undertook a city and site scale analysis, employing ecosystem modelling and spatial analysis, to compare urban brownfield and parks and quantify their regulating ecosystem service provision in urban, suburban, and peri-urban areas. Different land cover change scenarios were explored to illustrate potential changes in urban brownfield ecosystem service provision. Results showed that brownfield sites are a valuable component of green infrastructure, providing niche ecosystems and significant regulating ecosystem service provision, especially in densely built urban areas. Many types of brownfield have scope to be managed or modified in the meantime to maintain or increase urban resilience. Findings highlight the lack of urban park space and the potential of brownfield to provide additional urban green space and ecosystem services as urbanisation continues.

Objective 2 provided several **contributions to knowledge. First**, these findings extend current knowledge about park and brownfield ecosystem service provision, contributing useful information to existing urban ecosystem service research. The quantification and comparison of regulating ecosystem services of urban brownfields and parks provides a novel insight into the ecosystem service provision across an entire urban environment. It is clear from existing literature that urban green spaces and green infrastructure contribute to ecosystem service provision and resilience in urban areas. However, the important role of brownfields has been identified through this study, which highlights the current and potential value of brownfield land to urban resilience. **Second,** the direct comparison of parks and brownfield typologies is a novel approach and findings add to current knowledge by demonstrating the contrast in distribution and ecosystem service provision of parks and brownfields in highly urbanised areas. **Third**, the approach adopted in this study identified urban areas with inequity in park space and an abundance of brownfield land, which could be modified to provide socio-ecological benefits where they are most needed. Thus, this research contributes useful information for the sustainable planning and management of brownfields, and supports strategic redevelopment practices, to prevent loss of urban ecosystem services in the drive for urban resilience.

6.4 Objective 3: Summary and contributions to knowledge

Objective 3: To investigate the spatial dependency between brownfield and at-risk communities and make recommendations for the most effective use of brownfield land to enhance urban resilience (**Chapter 5**).

- Increased social vulnerability to environmental hazards was more prevalent in densely built urban areas.
- Many spatial hotspots of increased brownfield area, social vulnerability and environmental hazard exposure were identified in urban regions.
- Neighbourhoods with acute social vulnerability contain, on average, eight times more brownfield land cover than those with very low social vulnerability.
- With increased social vulnerability and environmental hazard exposure, the proportion of many individual brownfield types in neighbourhoods increased.
- Four key recommendations for planning policy and practice were made, with optimal recommendations identified for each brownfield type. These included strategic greening opportunities, the removal of impervious surfaces, enabling public access and redevelopment avoidance.
- Irregular shape and vegetated, highly vegetated supplementary or enclosed, and scrub grassland provide the greatest environmental benefits in areas of increased social vulnerability and exposure to environmental hazards. Redevelopment of these types should be avoided, and dependent on contamination, public access could be provided.

- Two brownfield types impervious grey surfaces, and functional and civic grey spaces, were identified as having the greatest potential to aid urban resilience if impervious surfaces are removed and strategically greened.

A review of the literature identified a paucity of evidence concerning the spatial relationship between brownfield and at-risk communities from a socio-ecological perspective. Research integrating brownfield ecosystem service models into brownfield redevelopment evaluation is an emerging field (Kolosz et al., 2018), and is lacking consideration of different types of brownfields. Consequently, much uncertainty exists regarding the potential of brownfields to lessen exposure of at-risk communities to environmental hazards in urban areas. This research addressed these gaps. Specifically, it explored the spatial and statistical intersection between environmental hazards (flood risk and air pollution), social vulnerability, and brownfield extent. Drawing on the findings presented in **Chapters 3 and 4**, **Chapter 5** (**Objective 3**) explored how a typology of brownfield land could potentially enhance urban resilience to environmental hazards. Findings show that brownfields currently and have great potential to enhance urban resilience, based on their location, physical status, and relationship with several key aspects related to resilience of the urban system. Typically, the amount of brownfield in a neighbourhood increases linearly as social vulnerability increases. A significant number of hotspots were identified where the spatial distribution of at-risk communities, increased brownfield extent and environmental hazard exposure coincided.

Further, the results identified that increased social vulnerability and environmental hazard exposure correspond spatially with an increased proportion of several specific types of brownfield. Recommendations for planning policy and practice were made for each type of brownfield based on their spatial associations with social vulnerability and environmental hazards, ecosystem service provision, and perviousness. Identifying spatial interactions between brownfields and at-risk communities from a socio-ecological perspective is important. This provides a better understanding of the potential positive or negative consequences of urban redevelopment processes. Identifying strategic redevelopment or modification opportunities for brownfields may benefit at-risk communities through hazard alleviation, planning adaptation and resilience actions in urban areas.

There are several **contributions to knowledge** resulting from achieving **Objective 3**. **First**, using a novel approach to identify associations between social vulnerability and environmental hazard exposure, this research adds to existing knowledge by providing an assessment of different types of brownfield ecosystem value and/or redevelopment potential at a city scale.

Second, to the authors best knowledge, this study presents the first attempt to provide recommendations to enhance urban resilience at the city-scale based on current and potential socio-ecological value of different brownfield types. This provides useful information and may be generalised for these types and apply to other cities, where many socio-economically deprived, ethnically diverse populations and those with health inequities reside (Galea, Freudenberg, & Vlahov, 2005; Glaeser, Kahn, & Rappaport, 2008). **Third**, this research provides evidence and recommendations for strategic redevelopment and modification of Greater Manchester brownfield where environmental inequality and inequity exists.

6.5 Research critique and further lines of enquiry

The research and findings in this thesis provide a novel study of brownfields' contribution to urban resilience, however, some limitations were identified, and further research to take this study forward would be beneficial. The main limitations for the thesis are discussed here.

The quality of existing geospatial datasets utilised in analysis may not always encompass all data for a specific area, for example, **brownfields and parks may exist that have not been identified in the data**. This was limited by the creation of an updated brownfield spatial dataset (**Chapter 3**), and obtaining the park data from Ordnance Survey, a reputable source. Further research could investigate the potential of Ordnance Survey topography data themes (e.g. roads, buildings, gardens), and associated text and identification features (Ordnance Survey, 2017a) to identify brownfield land. Such research could exclude known urban features, ascertain land use changes, and identify land parcels as potential brownfield land not reported in current databases.

Brownfield identified as potentially environmentally beneficial in this research may be contaminated. Due to the absence of any robust or comprehensive information on contamination, such investigation was beyond the scope of this thesis. Contaminated areas of a site may previously have been capped with tarmac/concrete to prevent local airborne exposure to contaminated dust particles (Hollander et al., 2010). The recommendations of surface disaggregation and strategic greening of contaminated sites can, however, be useful in allowing phyto-remediation to occur if certain tree and other plant species are present, particularly *Salix* and *Betula* (French et al., 2006) (a common brownfield species). Further research to explore the incidence of contamination on brownfield could, for example, evaluate the previous use (or identified future use) for a subset of low-risk sites and analyse soil and water samples for contamination.

Accuracy of the land cover classification undertaken in **Chapter 2 and 3** was high (94%) (>85% is acceptable according to Foody (2008)), however, the high-resolution **aerial imagery used** for the object based image analysis and supervised land cover classification **was several years old** and some land cover changes may have taken place in the meantime. Whilst the most up-to-date imagery (in 2018) was available for most areas, data for a limited number of sites was captured in 2009. To mitigate this field verification using up-to-date Google aerial imagery and Ordnance Survey topography layers gave a detailed indication of changes or development at each site between image capture date to present. As a next step, as more current (or near real-time) aerial imagery is made available, the analysis of trends in brownfield redevelopment could be analysed to establish the changes and loss of brownfield in our cities, and the investigation of temporal changes in land and vegetation cover on brownfields. This would reveal the spatiotemporal pattern and dynamics of urban brownfield in terms of both redevelopment and vegetation succession and enable assessment of the associated changes to ecosystem service provision.

The use of i-Tree modelling tools meant that **only trees and tree canopy cover could be included to estimate ecosystem service provision**. Soil, water, and herbaceous vegetation also contribute to urban ecosystem services (Francis & Chadwick, 2013); however, trees are the most significant contributor of regulating ecosystem service provision in urban land uses (Bolund & Hunhammar, 1999; Elmqvist et al., 2016). Future research focussed on further ecosystem services provided (other than those investigated here) by the full range of land cover types identified on brownfield would provide a broader overview of brownfield potential to aid urban resilience, as would the exploration of ecosystem dis-services which are generally under-studied (Blanco, Dendoncker, Barnaud, & Sirami, 2019).

The research here focussed on a subset of regulating services identified as important in the case study area. The potential of brownfield to lessen exposure to other climate and environmental hazards would further advance the research here. For example, recent research has identified disproportionate exposure to urban heat island intensity in areas where more ethnic minorities reside, and poverty is more widespread (Hsu, Sheriff, Chakraborty, & Manya, 2021). A lack of urban green space, and more impervious surface and structures are a key contributor to this inequity (Hsu et al., 2021). With the new understanding of the relationship between brownfield and local community settings presented in this research, brownfields should be seen as a more positive resource in the future.

The research undertaken identified four main dimensions of social vulnerability, whilst this gave a broad overview of social vulnerability in the study area, these dimensions are not all encompassing, and **other characteristics of individuals or communities may result in vulnerability**. The issue of ecological fallacy remains regarding the scale at which social vulnerability and environmental hazard risk were analysed (LSOA), and **data was not indicative or representative of all people** or communities that reside within them. This could be addressed with finer scale analysis of post codes or individual households, those within areas of known flood risk, citizen science recording for air pollution exposure, and proximity to brownfield type. Further research could also examine spatiotemporal trends in social vulnerability. Using historical data to construct social vulnerability indexes and the key dimensions could monitor temporal changes and shifts in area based socio-economic and demographic trends as urban densification is impacted by brownfield and other redevelopments. This could also track environmental inequity over time, for example is green space access improving or exposure to environmental hazard more equitable (Hsu et al., 2021).

6.6 Implications for policy and practice

This research highlights several implications for policy and practice which could ensure the best possible use for brownfields. These are presented below.

1. **Policymakers and practitioners should be aware of limitations in brownfield databases when used.**

A comprehensive up-to-date brownfield database was produced in this study. This highlighted that existing databases used in planning policy are not all-encompassing. Ideally, national policy should be introduced as a priority for local authorities to once again report information on brownfield (similar to NLUD-PDL). This is essential for determining the best strategic use of brownfield land to aid urban resilience.

2. **Urban planners should take note of the diversity of brownfield types that exist, the range in land cover types and ecosystem service provision, and that brownfield is not a single entity.**

A better understanding of the specific physical characteristics of brownfields was completed. The spatial configuration and physical status of brownfield sites across the city, and their potential ecosystem service provision, should be considered whilst being flexible in the redevelopment of brownfields (Mathey et al., 2015).

3. **The loss of ecosystem services in the redevelopment of brownfield should be considered in new development plans, and ecosystem services should be offset, and alternative opportunities explored.**

The substantial ecosystem service provision by brownfields was illustrated in this research which are shown to have significant further potential if modified. The loss of brownfield ecosystem services should be considered in new development plans, and offset, similar to biodiversity offsetting/net gain approaches, to compensate for any losses in development (Defra, 2019), and alternative opportunities should be explored and considered for sites where redevelopment is unlikely to take place straightaway. Identifying the spatial distribution and potential ecosystem service provision of brownfields, and redevelopment patterns within an urban system, could provoke policy debate regarding the impacts of large-scale surface scraping, and end-use conditions as brownfields are abandoned, demolished, or indeed redeveloped.

4. **Strategic redevelopment practices should be installed.**

The environmental context of brownfields, and how they relate to socio-ecological factors in urban systems was identified. This highlighted the significant spatial relationship between brownfields, at-risk communities, and exposure to environmental hazards. Brownfields should be selected based on their location, physical status, and relationship with several key aspects related to resilience of the urban system. This is important to prioritise redevelopment where the least impacts to urban resilience are realised, and green-infrastructure present on brownfield is retained or enhanced where it is most beneficial for locality and function.

5. **Upon abandonment sites should undergo surface preparations to improve opportunities and public use encouraged.**

Surface preparations may improve opportunities for interim or alternative uses or enhance chances of natural vegetation succession taking place (Bazzaz & Bazzaz, 1996; Schadek, 2006). Furthermore, simply leaving a site open, or applying minimal modifications to some brownfield sites can encourage public use (Rall & Haase, 2011). Ensuring the interim function of brownfields as ecosystem service rich green spaces, or community assets could help to address some of the risks to human health and wellbeing associated with urban densification. As identified in this thesis, many brownfield sites coincide spatially with the communities most vulnerable to environmental hazards, and in particular those in the most diverse, densely populated, economically deprived areas. This could be achieved with the selective and strategic redevelopment of brownfield contingent on their location, distribution, and characteristics.

6. A rapid ecosystem service assessment tool is needed.

Beyond preliminary ecological appraisal and phase one habitat surveys, which examine biodiversity and ecological aspects of brownfield sites before development, it is recommended that a rapid ecosystem service assessment tool is needed to support practice. This may alleviate the clearance of tree stock and loss of ecosystem services on brownfield (observed during this research) and allow like-for-like replacement. This tool could allow the rapid assessment of brownfields from a socio-ecological standpoint and be applied to identify and classify brownfield, provide textual and visual information, deliver estimated ecosystem service provision, suggest potential re-use options for interim use, and allow scenario analysis using future projections of land cover impacts. Targeted decision-making processes in the planning, management, re-use, and renovation of brownfields could be aided by such a tool, or at least provide knowledge of these issues, provoking thoughts and conversation by planners, policy makers and stakeholders. This is important in order to provide more access to open public space or limit the destruction and removal of trees and vegetation during redevelopment or maintenance of brownfield and thus, ensure sustained ecosystem service provision, and urban resilience, especially in socially vulnerable areas already encountering environmental injustice.

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Appendices

Appendix 3.1 Brownfield typology clustering method

An example of how the formation a three-level hierarchical typology operates is as follows: The dataset is assessed for optimal starting cluster solution, and the *k*-means algorithm is run on the whole data set producing *n* clusters. These are then separated into individual datasets. These cluster datasets form the highest level of the hierarchy. Each of these datasets is again clustered using k-means (after initial starting cluster solution is defined), forming another *n* clusters each which form the next level of the hierarchy. Dissimilarity is assessed after each cycle. A flow chart is presented below along with an idealised example of how the hierarchical typology can form (Fig. A3.1.1 & A3.1.2), however this uses data for 2400 brownfields and represents an exact cluster split of the data at each level of clustering, without the merging of similar groups or formation of small distinct groups that form during the process. The process may lead to two or more clusters forming at each level depending on the performance during the analysis for optimal cluster solution.

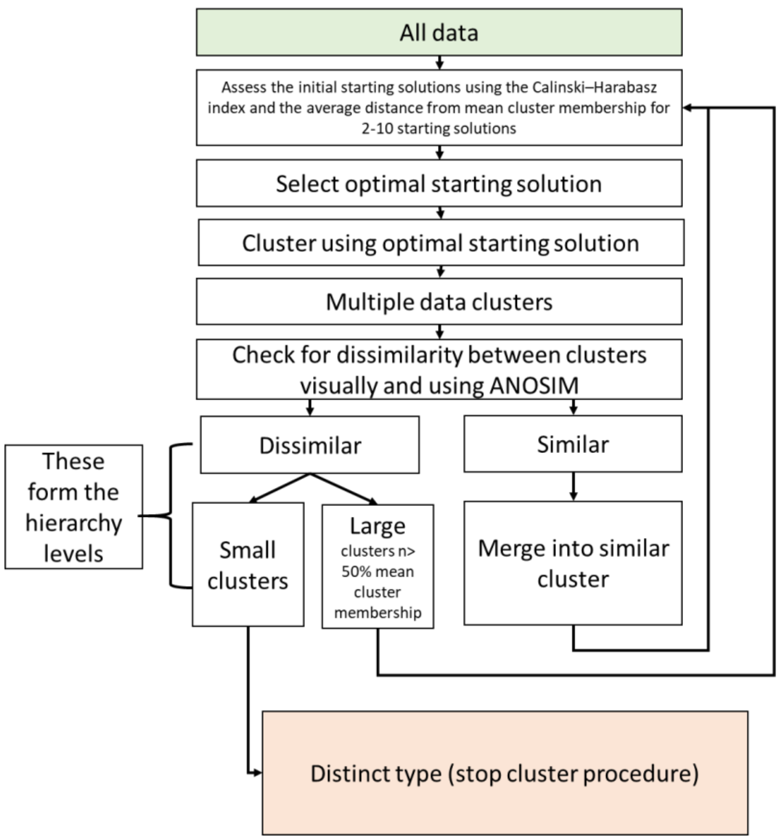

Figure A3.1.1: Repeated cluster analysis process resulting in a three hierarchical levels

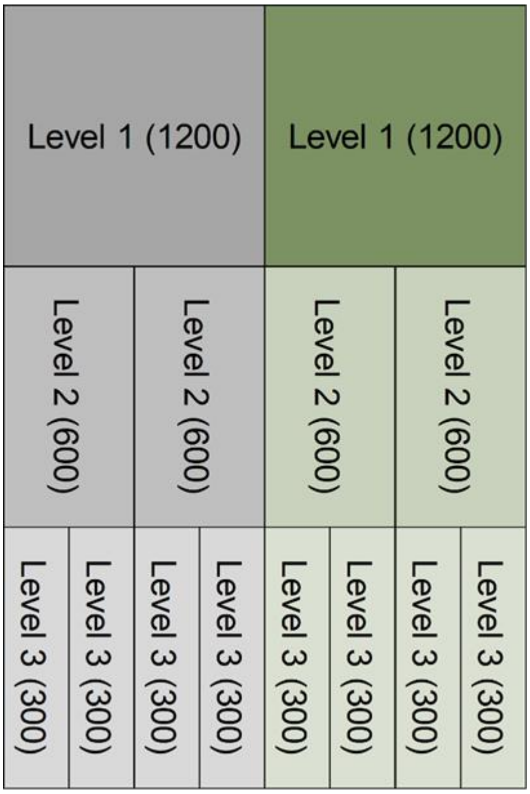

Figure A3.1.2: A hypothetical example of a three-level hierarchy. Number of brownfield sites in brackets.

Appendix 3.2 Brownfield typology description

Table A3.2.1 presents description for each brownfield type based on interpretation of aerial imagery, land cover and landscape metrics.

Table A3.2.1: A brief description of each type of brownfield identified in the typology

Brownfield typology	**Description of notable characteristics**
(a) Buildings	This highly impervious brownfield type is comprised of a small built structure, either encompassing the entirety of the site or containing a very small area of hard surfaced area, such as an access way, path, or yard. These sites are compact, and mainly regular in shape in densely populated urban areas. These may be unused or developable residential or commercial properties and contain negligible vegetation cover.
(b) Compact commercial units	Small, compact, and regularly shaped impervious sites, which typically contain one-third hard surface cover and two-thirds built structure. These sites contain little or no vegetation, or other pervious surfaces, and are mainly located in urban and suburban areas. The sites tend to be for commercial use with external parking or storage areas.
(c) Impervious grey surfaces	Situated mainly in urban areas, these sites are almost entirely impervious. Either total coverage, or a large proportion of man-made hard surface cover may exist at these small sites, and the presence of a relatively small structure may be evident. These compact and level sites are the most abundant type of brownfield, and include tarmacked parking areas, concrete slab storage yards, and other hard surfaces. Little or no vegetation is present.
(d) Industrial units with yards	These sites are typically highly impervious comprising of large industrial units and associated hard surface coverage, usually storage yards and parking areas. Mostly situated in urban and suburban areas, these areas are level and compact in character. Small amounts of canopy cover may

Brownfield typology	Description of notable characteristics
	be present, either as aesthetic vegetation in parking areas, or on small unfrequented areas of land to the periphery of the site.
(e) Functional and civic grey space	These sites are characterised by a large hard surfaced area with built structures. Boundary or barrier vegetation and trees exist between internal impervious areas, or along the perimeter of the site. Mostly flat surfaces occurring in regular and irregular shapes with evidence of commercial or functional use, such as office buildings and associated facilities, car parks with aesthetic vegetated areas.
(f) Large Dilapidated Industrial or Commercial	Typically located in central urban areas, these sites are large built-up industrial, commercial, or mixed-use areas in need of regeneration. They are largely impervious areas with numerous built structures, roads, and parking and storage areas. Some vegetation exists as street trees, grass verges, or other informal vegetated areas. Both regular and irregularly shaped sites are common, with a characteristically level topography.
(g) Built with water body	Mainly occurring in urban areas, these sites typically consist of large industrial or commercial structures and associated hard surfaces with a relatively small water body, most likely a remnant from historical industrial practices. Trees are commonplace adjacent to the water body. These sites have a relatively level topography (excluding land close to the water edge), regular shape, and large impervious footprint.
(h) Industrial with peripheral vegetation	Typically, these sites contain a large industrial or commercial building, associated hard surfaces, and with an unused area which may have some disturbed ground with natural succession taking hold. These sites often display mid-to-late vegetation succession with mature trees, shrubs, and

Brownfield typology	Description of notable characteristics
	scrub vegetation present. Mainly located in urban, and suburban zones, with a compact shape, and level surface.
(i) Hard surfaced with peripheral vegetation	Sites with a high percentage of impervious hard surfaces, including tarmacked areas, building foundations and concrete slab surfaces, exhibiting trees along the boundary of the site. Mainly situated in urban and suburban areas, these sites are compact with a regular shape and level surface. A small amount of early pioneer vegetation may be present situated around the understory of the treeline, and demolished building footprints.
(j) Large industrial with peripheral vegetation	These sites with a mid to large area (2.5ha to 15ha) may contain multiple, large commercial/industrial structures, large impervious surface area. Parcels of pervious ground and vegetation may exist throughout. One or more boundaries may contain tree canopy. Located mostly in urban areas, however distributed throughout the landscape, these sites may be complex in shape, with areas of uneven topography in parts.
(k) Built with managed or pioneer vegetation	Distributed mainly in suburban areas, these sites contain areas of pioneer, short perennial grass, and grass-herb communities, including regularly managed (or amenity) grasslands. These sites may contain hard surfaced areas and/or built structures and are generally less than 2.5ha. Introduced tree cover is also common, as are self-seeded species on sites with early successional areas of short vegetation. These sites can be both regular and irregular in shape with a level topographic profile.

Brownfield typology	Description of notable characteristics
(l) Hard surface with disturbed ground	These small to mid-size sites (up to 3.5ha), are characterised by hard surfaced areas, and predominant areas of disturbed ground. These sites can be recently demolished, disturbed, surface scraped, or contain activities involving bare earth movement. Early vegetation succession may be present on areas of exposed surface, or more mature vegetation at the site perimeter. Impervious areas can be building remnants, foundations, and infrastructure. These sites are mostly compact with a level topography, and present primarily in urban and suburban areas.
(m) Properties with mud-successional vegetation or remnant gardens	Existing mainly in the less populated suburbs (though found elsewhere) these sites display a high percentage of vegetation cover, with remaining landcover comprising hard surface, and built structures. These may be larger commercial properties with mid-successional vegetation, and former (or developable) residential properties with remnant garden vegetation surrounding buildings and surfaces left over from previous uses. In terms of canopy cover, it is generally dominant over grass-herb communities. These areas tend to be compact and level sites but may have sloped topography adjacent to roads, rivers, canals etc.
(n) Site remnants and foundations with successional vegetation	The footprints of previous developments are most often found at these sites. Bare earth at the junctions of the foundation slabs, or exposed areas of rubble and bare earth allow natural succession to take place. Pioneer grass-herb communities, and self-seeded trees are also abundant in these areas. Most sites are small, compact, and regularly shaped, and located in suburban areas.
(o) Uneven and vegetated	With a steep gradient present on at least part of the site increasing their mean slope, these sites contain embankments which tend to be adjacent to past or present transport infrastructure, including roads, railways, and waterways. The remainder of the site is level and holds the man-made

Brownfield typology	Description of notable characteristics
	structures from previous development. An exception to this is disused railway tracks which most often contain two steep embankments with a central linear trackway which held the previous infrastructure. These sites have a high vegetation percentage, mostly located on the unlevel topography.
(p) Irregular shape and vegetated	Highly irregularly shaped sites with a high perimeter-area ratio, often situated on infill land between developments of residential and/or commercial properties from different periods. These sites tend to be highly vegetated (possibly due to lack of access) and predominantly situated in suburban and urban zones.
(q) Disturbed and vegetated	A main feature of these sites is relatively large areas of exposed earth (>25%), with vegetation also present. Mainly located in urban and suburban areas, these sites may also contain some hard surface cover left from previous use. The large percentage of bare earth may be rubble and soil left over from demolition, surface scraping, earth movement activities, or contamination, preventing vegetation growth. A level topography and compact shape are also common. Vegetation succession has most often taken place on the exposed surface cover and along site boundaries.
(r) Vegetated with water body	This uncommon type of brownfield site is distributed across the urban environment and typically contains a small water body and high percentage of vegetation. Evidence of past industrial activities are present in the form of building foundations and infrastructure, and trees shrubs, and bushes are distributed across the sites, though more commonly adjacent to the water body. These are highly pervious sites, with an irregular shape and unlevel topography adjacent to the water feature on site.

Brownfield typology	Description of notable characteristics
(s) Urban pioneer vegetation and amenity grassland	Sites with an extensive coverage of grass-herb vegetation communities, with small areas of hard surface cover. These areas can be sites where pioneer vegetation succession has taken hold on shallow topsoil formed on demolished sites, or closely mown amenity grassland, such as bowling greens, and former school, and recreational grounds. Typically located in the suburbs, these sites are small, level, and compact in shape.
(t) Scrub grassland	Abundant vegetation growth across much of the site, including grasses, shrubs, bushes, and tree species. These highly pervious sites can include verges and informal greens, usually separating roads from residential properties, and infill land between urban developments. Verges and greens may be managed vegetation, whilst scrub-grassland is dominated by spontaneous vegetation growth, though both contain similar ratios of grass-tree coverage. These sites are mainly situated in suburban areas and may have uneven topography and regular shapes.
(u) Informal open grassland	An open green space almost entirely covered with grass-herb vegetation, which may contain marginal tree cover at the perimeter or occasional trees in the interior of the site. These spaces tend to be flat surfaced, and regularly shaped sites located mostly in suburban areas.
(v) Large open vegetated	Large sites with abundant spontaneous vegetation succession, these sites are greater than 6ha, may contain areas of bare earth, and water, and are highly pervious sites. They are mostly situated in peri-urban areas but can be found in built-up areas. A complex shape is frequent with areas of uneven topography across the site also common.
(w) Utilities, mill ponds and lodges	Small sites, with water body contained centrally, with tall vegetation and tree canopy surrounding the water edge. These sites may contain paths and tracks along one or more margins, suggesting public use. Both

Brownfield typology	Description of notable characteristics
	regular and irregular in shape, with steep banks leading to the water's edge. These sites are most likely remnants from past historical activities requiring a water source to be productive such as mills, factories, dye works etc.
(x) Highly vegetated supplementary or enclosed	These sites comprise relatively large expanses of vegetation either surrounding or adjacent to small areas of hard surfaces, structures, or disturbed ground. Distributed throughout the urban area, these sites range from small compact sites to large areas with remnants of previous activities. They can be both regular and irregular in shape with an uneven surface.
(y) Densely vegetated	A highly vegetated pervious surface, dominated by canopy cover, characterises this brownfield type. Scrub grassland vegetation may also be present, with little presence of impervious surfaces, water, or bare earth. Situated throughout suburban and peri-urban areas these sites are relatively small and compact areas, with some uneven topography.
(z) Very large open green space	Encompassing considerable hectarage (>30ha) in a peri-urban setting, these areas contain a large amount of vegetation, mostly grass with tree canopy along boundaries. Areas of water and bare earth are also common with some peripheral man-made structures and surfaces. A complex site shape, and areas of uneven topography are evident, though the large site size reduces mean slope results relative to smaller sites.

Appendix 3.3 Aerial imagery examples of the brownfield typology

Figure A3.3.1 presents examples of high resolution (25cm) aerial images for each park type identified. Refer to Appendix 3.2 for type names.

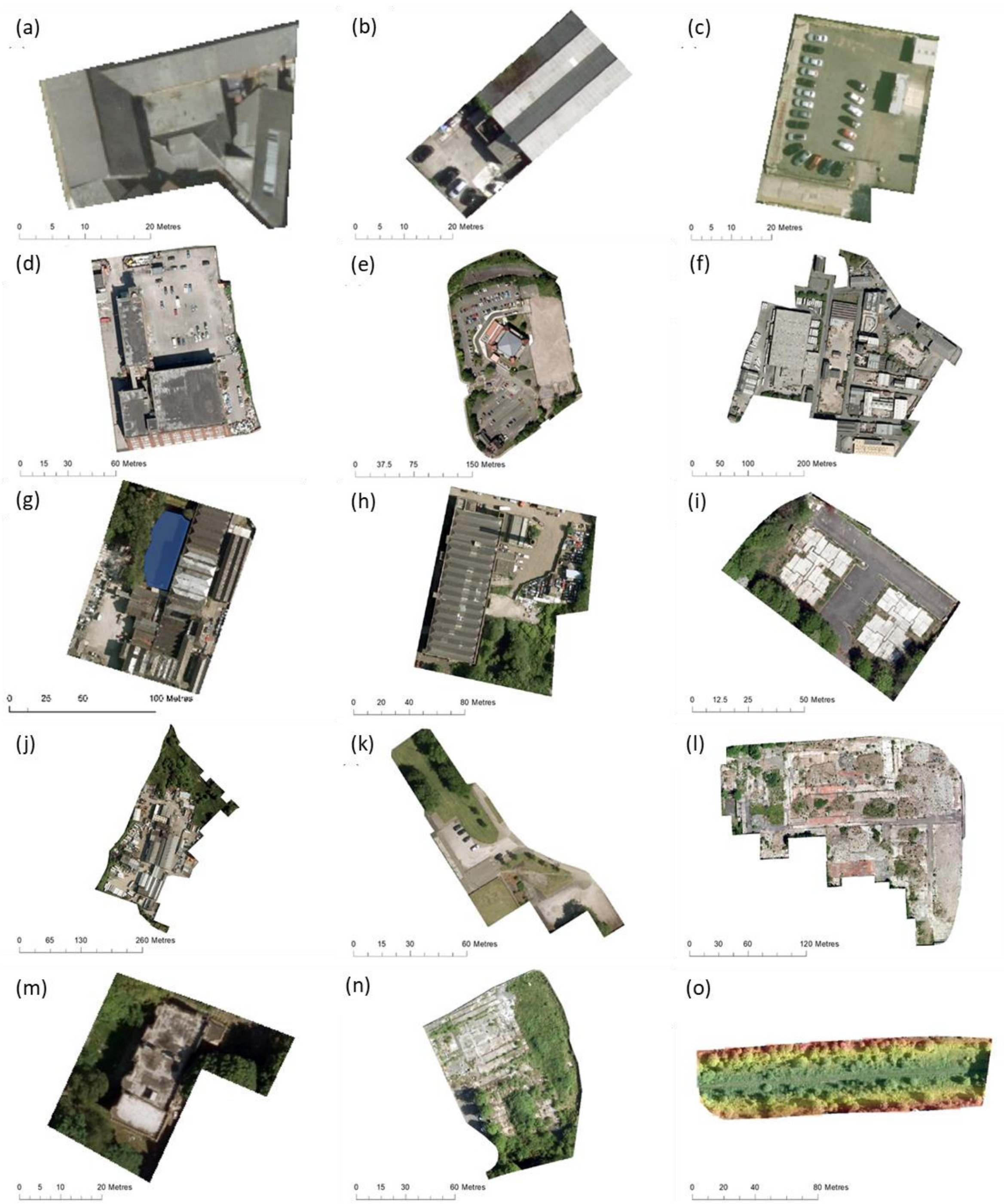

Figure A3.3.1: Aerial image examples of each brownfield type in the typology

Appendix 3.3 continued

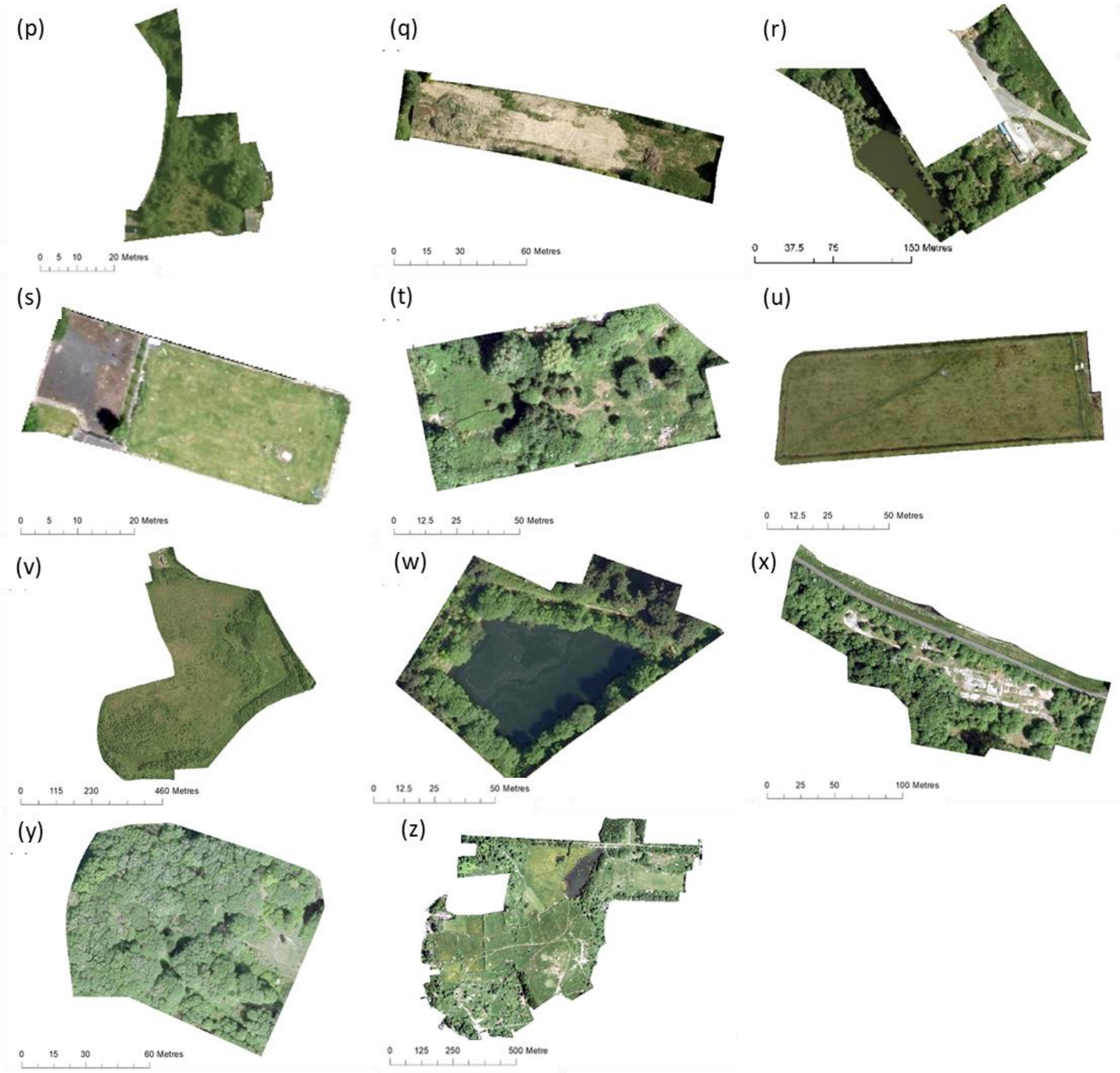

Figure A3.3.1 continued: Aerial image examples of each brownfield type in the typology. Images: (Getmapping, 2018)

Appendix 4.1 Park typology descriptions and aerial imagery

Table A4.1.1 presents description for each park type based on interpretation of aerial imagery, land cover and landscape metrics.

Table A4.1.1: Park typology description

Park typology	Description of notable characteristics
(a) Hard play parks	Large extent of hard surface construction materials used for play or recreation facilities or piazza. Areas of amenity grass and few trees may be present. Generally small and regular in shape and level surface topography.
(b) Recreational grounds and gardens	Generally small formal parks with high canopy cover at the perimeter and along multiple hard surfaced paths, and a circular hub containing a formal feature is often present increasing the imperviousness of this type. Flower beds are common and occasional sports facility may be present in the form of hard tennis court or bowling green. One of the smaller and impervious types, these are mostly regularly shaped and level parks.
(c) Large recreational grounds and gardens	Like recreational parks and gardens but with a larger surface area, more hard paths and multiple hubs allowing people to circulate in the park. Trees are present along the perimeter and segregating areas containing open grassland, sports courts, and bowling greens. Both regular and irregular in shape with level topography.
(d) Community parks	Small parks with a high amount of open amenity grassland. A hard-surfaced children's play area is most often present and tree canopy is mostly located around the perimeter of the park. Multiple impervious paths lead from multiple access points. These parks have the most level topography of all types and can be both regular and irregular in shape.
(e) Country and riparian parks	High continuous tree/shrub cover, irregular shape and the presence of water characterises this type. These parks often encompass a river or streams giving them the second highest presence of water of the park typology. An uneven topography is common at these large parks. Parking areas or impervious zones make up the hard surfaces rather than multiple pathways which may be obscured beneath the tree canopy.
(f) Multifunctional activity parks	These parks are characterised by the multiple areas for sports and play activities, often between 5 and 10 activity areas including football, cricket, crown green bowling, tennis, ball sports zones, playgrounds, and cycle tracks. These areas consist of large grass and hard surface areas. Trees are mostly located between activity zones and around the park perimeter. Generally level and regular in shape.
(g) Small wooded parks	A high tree/shrub cover is the dominant feature at these small green spaces. Between trees are small amenity grassland areas with few hard surfaces except pathways often obscured by the high canopy cover. These sites are relatively regular with level topography.
(h) Large forest parks	These large, forested parks are the most irregular in shape and contain large continuous areas of high tree canopy cover interspersed with grassland areas and contain sparse hard surface cover. Like country and riparian parks these often contain water bodies such as rivers and streams. These types of park have the most uneven topography of all parks.
(i) Green wood parks	These moderate to large parks contain the second highest prominence of grassland area, often with perimeter woodland and individual trees and copses internally. There is little presence of hard surfaces, few paths and negligible presence of water. Play and sports zones are absent, and the parks are mostly regularly shaped and level.

Park typology	Description of notable characteristics
(j) Water parks	These parks are characterised by the presence of large water bodies consisting of reservoirs and lakes. Additionally, a high percentage of tree cover is evident across the remainder of the parks punctuated with open grassland areas. Multiple paths or tracks are evident either along the water's perimeter or throughout. These parks are the most irregularly shaped, with some uneven topography.
(k) Grassland parks	Open grassland is the dominant feature of these moderately sized parks, often managed internally, with unmanaged grass borders at the boundary where tree presence is most likely. These spaces can contain football or cricket pitches and complex pathway networks are limited. These parks can be both regular and irregular in shape with some uneven topography.
(l) Under construction or modification	A high proportion of bare earth or disturbed ground is evident at these parks indicating a park under construction or modification. There is a low presence of tree cover or hard surfaces, and a relatively high grass/herbaceous vegetation content. This type can range in size and are the type with the second most level topography.

Figure A4.1.1 presents examples of high resolution (25cm) aerial images for each park type identified.

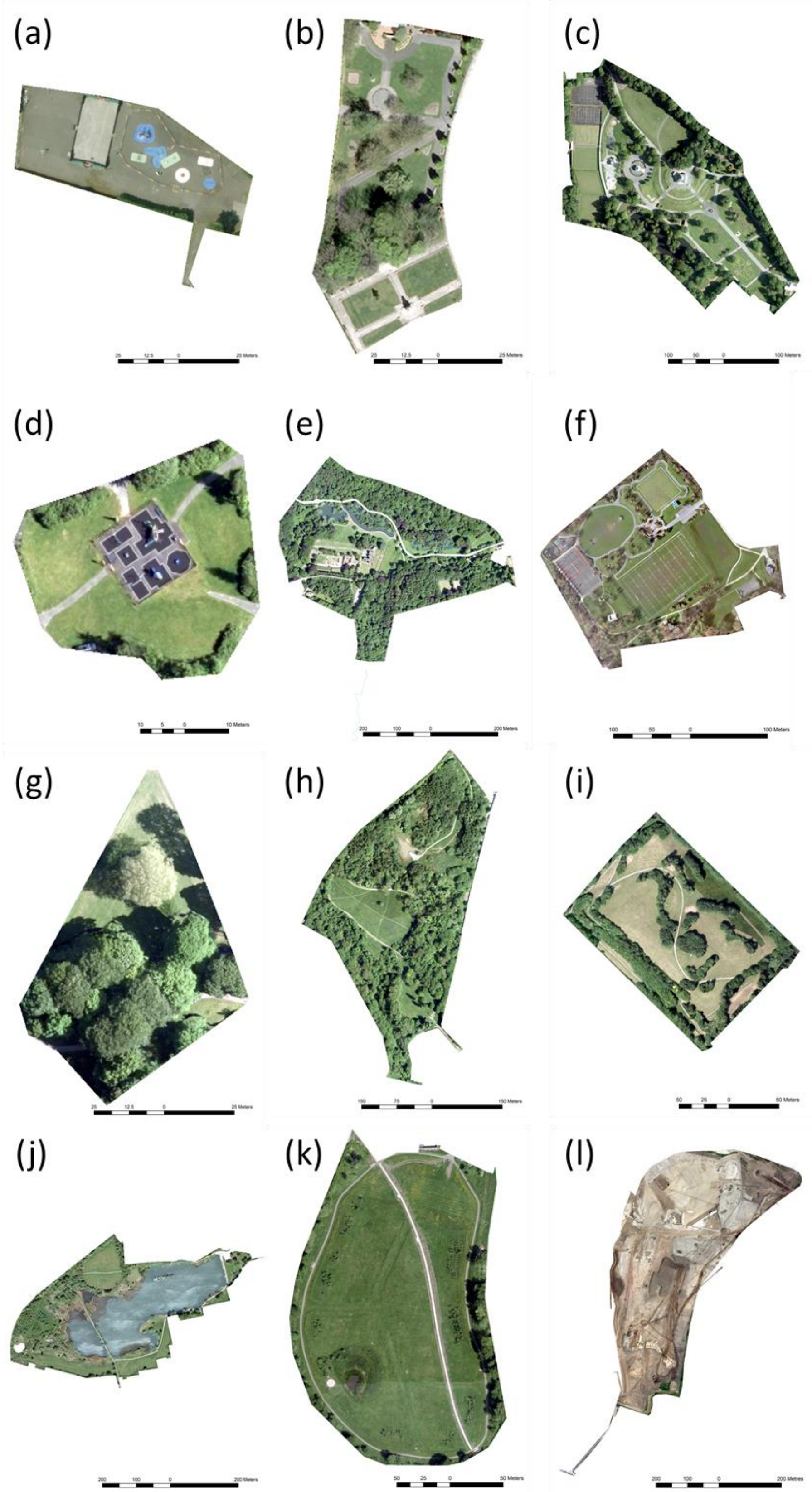

Figure A4.1.1: Aerial imagery of an example for each urban park type identified (description in Table 4.3). Images: (Getmapping, 2018)

Appendix 4.2 Individual air pollutant removal in urban areas

Table A4.2.1 presents estimated mean individual air pollutant removal for each brownfield and park type.

Table A4.2.1: Individual air pollutant removal by brownfield and park types annually in urban areas only.

Brownfield typology	Ozone removed annually (kg)	Nitrogen Dioxide removed annually (kg)	Sulphur Dioxide removed annually (kg)	Carbon Monoxide removed annually (kg)	PM >2.5µ and <10µ removed annually (kg)	PM <2.5µ removed annually (kg)	Total air pollution removed annually (kg)
(f) Large Dilapidated Industrial or Commercial	6,910.5	2,244.6	259.5	116.2	1,635.3	3.2	**11,169**
(v) Large open vegetated	3,279.8	1,065.3	123.1	55.1	776.1	1.5	**5,301**
(i) Hard surfaced with peripheral vegetation	2,721.5	884.0	102.2	45.8	644.0	1.3	**4,399**
(n) Site remnants and foundations with successional vegetation	2,714.7	881.8	101.9	45.6	642.4	1.2	**4,388**
(e) Functional and civic grey space	2,629.1	853.9	98.7	44.2	622.1	1.2	**4,249**
(h) Industrial with peripheral vegetation	2,112.8	686.2	79.3	35.5	500.0	1.0	**3,415**
(j) Large industrial with peripheral vegetation	1,861.4	604.6	69.9	31.3	440.5	0.9	**3,009**
(c) Impervious grey surfaces	1,728.4	561.4	64.9	29.1	409.0	0.8	**2,794**
(q) Disturbed and vegetated	1,649.0	535.6	61.9	27.7	390.2	0.8	**2,665**
(x) Highly vegetated supplementary or enclosed	1,636.6	531.6	61.4	27.5	387.3	0.8	**2,645**
(p) Irregular shape and vegetated	1,544.5	501.7	58.0	26.0	365.5	0.7	**2,496**
(y) Densely vegetated	1,397.1	453.8	52.5	23.5	330.6	0.6	**2,258**
(g) Built with water body	1,012.0	328.7	38.0	17.0	239.5	0.5	**1,636**
(m) Properties with mud-successional vegetation or remnant gardens	984.5	319.8	37.0	16.6	233.0	0.5	**1,591**
(d) Industrial units with yards	877.0	284.9	32.9	12.9	207.5	0.4	**1,416**
(o) Uneven and vegetated	638.6	207.4	24.0	10.7	151.1	0.3	**1,032**
(t) Scrub grassland	297.0	96.5	11.2	5.0	70.3	0.1	**480**
(z) Very large open green space	253.8	82.4	9.5	4.3	60.1	0.1	**410**
(w) Utilities, mill ponds and lodges	185.6	60.3	7.0	3.1	43.9	0.1	**300**
(k) Built with managed or pioneer vegetation	162.5	52.8	6.1	2.7	38.4	0.1	**263**
(l) Hard surface with disturbed ground	145.7	47.3	5.5	2.5	34.5	0.1	**236**
(r) Vegetated with water body	115.7	37.6	4.3	1.9	27.4	0.1	**187**
(s) Urban pioneer vegetation and amenity grassland	112.4	36.5	4.2	1.9	26.6	0.1	**182**
(u) Informal open grassland	72.7	23.6	2.7	1.2	17.2	0.0	**117**
(b) Compact commercial units	36.5	11.9	1.4	0.6	8.6	0.0	**59**
(a) Buildings	19.6	6.4	0.7	0.3	4.6	0.0	**32**
Brownfield total	**35,099**	**11,400**	**1,318**	**588**	**8,306**	**16**	**56,727**
Park typology							
(h) Large forest parks	3,060.2	994.0	114.9	51.5	724.2	1.4	**4,946**
(f) Multifunctional activity parks	902.7	293.2	33.9	15.2	213.6	0.4	**1,459**
(b) Recreational grounds and gardens	820.1	266.4	30.8	13.8	194.1	0.4	**1,325**
(j) Water parks	567.7	184.4	21.3	9.5	134.3	0.3	**918**
(e) Country and riparian parks	490.4	159.3	18.4	8.2	116.0	0.2	**793**
(c) Large recreational grounds and gardens	480.0	155.9	18.0	8.1	113.6	0.2	**776**
(i) Green wood parks	302.2	98.2	11.3	5.1	71.5	0.1	**488**
(d) Community parks	81.0	26.3	3.0	1.4	19.2	0.0	**131**
(g) Small wooded parks	35.8	11.6	1.3	0.6	8.5	0.0	**58**
(l) Under construction or modification	22.2	7.2	0.8	0.4	5.3	0.0	**36**
(a) Hard play parks	19.5	6.3	0.7	0.3	4.6	0.0	**32**
(k) Grassland parks	3.0	1.0	0.1	0.1	0.7	0.0	**5**
Park total	**6,785**	**2,204**	**255**	**114**	**1,606**	**3**	**10,966**

Appendix 4.3 Tree species composition on Greater Manchester Land uses

City of Trees completed the largest i-Tree Eco survey (2018) in Greater Manchester encompassing approximately 2000 plots, completed by 57 surveyors. The tree composition for each land cover type was calculated by the author of this thesis (Table A4.3.1)

Table A4.3.1: Tree species composition on Greater Manchester land use types. Data: (City of Trees Manchester, 2018b). It must be noted that data collection did not incorporate the brownfield dataset used in this research. The category, "other", and land that does not fit into any other land use contained several plots on brownfields with no trees present.

Rank	**Agriculture**	%	Rank	**Cemetery**	%
1	Oneseed hawthorn (*Crataegus monogyna*)	13.8	1	Sycamore maple (*Acer pseudoplatanus*)	24.0
2	Goat willow (*Salix caprea*)	11.2	2	Common lime (*Tilia x europaea*)	16.0
3	English oak (*Quercus robur*)	10.0	3	English oak (*Quercus robur*)	12.0
4	Sycamore maple (*Acer pseudoplatanus*)	9.7	4	European ash (*Fraxinus excelsior*)	12.0
5	Silver birch (*Betula pendula*)	8.9	5	Leyland cypress (*Cupressocyparis leylandii*)	12.0
Other	Other	46.4	Other	Other	24.0
Rank	**Commercial/industrial**	%	Rank	**Golf course**	%
1	Sycamore maple (*Acer pseudoplatanus*)	10.5	1	English oak (*Quercus robur*)	23.4
2	Silver birch (*Betula pendula*)	8.2	2	Silver birch (*Betula pendula*)	8.5
3	Goat willow (*Salix caprea*)	8.0	3	Sycamore maple (*Acer pseudoplatanus*)	7.1
4	Oneseed hawthorn (*Crataegus monogyna*)	7.7	4	European beech (*Fagus sylvatica*)	6.7
5	Sweet cherry (*Prunus avium*)	7.1	5	European larch (*Larix decidua*)	6.0
Other	Other	58.5	Other	Other	48.2
Rank	**Institutional**	%	Rank	**Multi-family residential**	%
1	Sycamore maple (*Acer pseudoplatanus*)	16.7	1	Sycamore maple (*Acer pseudoplatanus*)	23.3
2	European ash (*Fraxinus excelsior*)	15.3	2	European black elderberry (*Sambucus nigra*)	10.0
3	White willow (*Salix alba*)	11.1	3	European ash (*Fraxinus excelsior*)	6.7
4	Silver birch (*Betula pendula*)	9.7	4	Norway maple (*Acer platanoides*)	4.4
5	European mountain ash (*Sorbus aucuparia*)	8.3	5	Oneseed hawthorn (*Crataegus monogyna*)	4.4
Other	Other	38.9	Other	Other	51.1
Rank	**Park**	%	Rank	**Residential**	%
1	Oneseed hawthorn (*Crataegus monogyna*)	10.7	1	Leyland cypress (*Cupressocyparis leylandii*)	23.6
2	European alder (*Alnus glutinosa*)	10.6	2	Oneseed hawthorn (*Crataegus monogyna*)	6.1
3	European ash (*Fraxinus excelsior*)	10.1	3	Port orford cedar (*Chamaecyparis lawsoniana*)	6.1
4	Silver birch (*Betula pendula*)	9.0	4	Sycamore maple (*Acer pseudoplatanus*)	5.9
5	Sycamore maple (*Acer pseudoplatanus*)	8.4	5	Sweet cherry (*Prunus avium*)	4.3
Other	Other	51.2	Other	Other	53.9
Rank	**Transportation**	%	Rank	**Utility**	%
1	English oak (*Quercus robur*)	17.6	1	Oneseed hawthorn (*Crataegus monogyna*)	88.2
2	Oneseed hawthorn (*Crataegus monogyna*)	10.1	2	Goat willow (*Salix caprea*)	8.8
3	Sycamore maple (*Acer pseudoplatanus*)	9.1	3	Sycamore maple (*Acer pseudoplatanus*)	2.9
4	Sweet cherry (*Prunus avium*)	7.9	4		
5	European ash (*Fraxinus excelsior*)	6.9	5		
Other	Other	48.4	Other	Other	0
Rank	**Other and no clear intended use**	%	Rank	**Water/wetland**	%
1	European alder (*Alnus glutinosa*)	15.0	1.0	Oneseed hawthorn (*Crataegus monogyna*)	20.8
2	European ash (*Fraxinus excelsior*)	13.5	2.0	Sycamore maple (*Acer pseudoplatanus*)	20.8
3	European white birch (*Betula pendula*)	10.2	3.0	European alder (*Alnus glutinosa*)	8.3
4	Oneseed hawthorn (*Crataegus monogyna*)	9.0	4.0	European ash (*Fraxinus excelsior*)	8.3
5	European aspen (*Populus tremula*)	8.3	5.0	Goat willow (*Salix caprea*)	8.3
Other	Other	44.0	Other	Other	33.3