Urban climate change adaptation

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Urban climate change adaptation: Exploring the implications of future land cover scenarios

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Abstract

Different land cover futures will have contrasting implications for cities working to adapt to the changing climate. This paper explores this issue, reporting on the application of a scenario-based land use modelling case study focused on Greater Manchester in North West England. It highlights that the interplay between varied drivers of change has the potential to generate contrasting land cover futures for the city-region, which will in turn influence climate change adaptation ~~agendas~~prospects. The case study pays specific attention to green infrastructure cover, as this can enhance the capacity of urban areas to adapt to climate change by providing functions such as evaporative cooling and rainwater infiltration. The two scenarios analysed within this paper connect, broadly, to the contrasting processes of expansion and shrinkage that are shaping cities worldwide. Where cities are expanding, stimulated by economic growth and increase in population, the danger is that associated land use change will pressure existing green infrastructure resources with a detrimental impact on adaptive capacity. Cities that are shrinking, or experiencing relative decline in comparison to other cities, face a different set of issues. Here, the emergence of vacant land provides an opportunity to secure adaptive capacity benefits associated with green infrastructure. With the processes of expansion and shrinkage projected to continue to influence the global landscape of cities, this research highlights that strategies are needed to protect and enhance green infrastructure in both contexts in order to maintain and build adaptive capacity and moderate climate-related risks.

Keywords: Climate change; Adaptive capacity; Land use change; Urban; Green infrastructure; Scenarios

~~1.~~1 Introduction

The adaptive capacity of cities and urban areas, which relates to their ability to anticipate, moderate and manage climate change impacts, is influenced by features and characteristics of their landscapes. Urban land cover also affects climate change impacts. For example, urbanisation can influence hydrological processes and in turn affect the frequency and intensity of flooding events (EEA, 2012; Sun, Li, Fu, Li, & Tang, 2013). This paper focuses on urban adaptive capacity in the context of the green infrastructure sites and networks that surround, permeate and exist within cities and urban areas. This includes woodlands, river valleys, parks and gardens, for example. The role of green infrastructure in adaptation to climate change, for example via the provision ~~or~~of urban cooling and flood risk management functions, is increasingly recognised within policy making and research communities (e.g. European Commission, 2013; Gill, Handley, Ennos, & Pauleit, 2007). However, less is understood about how urban land use change, specifically concerning the nature and extent of green infrastructure coverage, may influence the adaptive capacity of cities and urban areas over time. This paper is focused on exploring this issue.

Urban land cover and land use characteristics are complex and dynamic over multi-decadal timescales (Allen, 1997), with processes of urban development and decay continually reshaping cities. Globally, some cities are growing and expanding whereas others are experiencing shrinkage and decline (Martinez-Fernandez, Audirac, Fol, & Cunningham-Sabot, 2012; McKinsey and Company, 2016; Sassen, 2001), influenced by dynamic processes including globalisation, deindustrialisation and demographic change (Hall, 1993; Martinez-Fernandez et al., 2012). Ruth and Coelho (2007) recognise that this complexity adds to the challenges associated with responding to climate change in urban settings. In this context, they suggest that scenarios capturing "…a wide range of influences on the behaviour of urban systems…" can be developed with stakeholders, and subsequently analysed using computer models, to support institutional learning and action (Ruth & Coelho, 2007: 3325). When creating climate change adaptation strategies, scenario planning can support decision makers in understanding and responding to the implications of divergent development pathways and contrasting future land use patterns on urban adaptive capacity. Despite the potential value of this approach, little research has been undertaken on this topic to date, and this paper aims to address this gap and support activities linked to the reduction of urban climate risk.

This paper considers how land use change over the coming decades, with a specific focus on green infrastructure, may influence the capacity of urban areas to adapt to extreme weather and climate change hazards such as flooding and heatwaves. A case study focused on Greater Manchester in North West England is utilised to explore these issues. Established scenario development and land use modelling methods are integrated to create two different future land use scenarios for Greater Manchester. The two scenarios represent contrasting ways that the city-region's urban centres and surrounding landscapes may evolve over the period to 2050. The scenarios are analysed and discussed to build understanding of how changes in land use, particularly green infrastructure, may influence Greater Manchester's adaptive capacity. Broadly, one scenario presents a future driven by growth and expansion, whereas the second scenario is characterised by processes connected to shrinkage and decline. Building on the research outputs, transferable insights are developed into approaches that can help to secure the long-term contribution that green infrastructure can make to building capacity to adapt to climate change ~~under different future scenarios for~~in urban areas.

~~2.~~2 Literature review

Given the severity of future climate change projections, and the increased risk of related impacts such as heatwaves and flooding (IPCC, 2013), greater emphasis must be placed on adapting urban areas to the changing climate. One aspect of adapting to climate change concerns maintaining and enhancing adaptive capacity. The Intergovernmental Panel on Climate Change (IPCC) positions adaptive capacity as one of the factors that determines the severity of climate-related risks, specifically as an element of vulnerability, which also incorporates the concept of sensitivity (or susceptibility to harm from) climate hazards (IPCC, 2014). Following the IPCC's approach, risk is therefore a function of climate hazards, the degree to which a receptor is exposed to a hazard and the vulnerability of the receptor to the hazard. Consequently, where adaptive capacity is high this acts to moderate the severity of climate-related risks by reducing vulnerability, although low adaptive capacity can therefore exacerbate risk.

Swart et al. (2012: 11) define adaptive capacity as "…the longer-term capacity to plan for preventing and/or managing the impacts of climate change". The European Environment Agency adds that adaptive capacity relates to "…a set of enabling conditions…" that support adaptation to climate change impacts (EEA 2012: 63). Adaptive capacity is determined by a wide range of interrelated issues, including societal characteristics (e.g. citizens' awareness of climate change), land use (e.g. the extent of green infrastructure coverage), and institutional factors (e.g. the existence of strategies and governance frameworks related to adaptation) (Haddad, 2005; Smit & Wandel, 2006; Swart et al., 2012; Yohe & Tol, 2002).

Although urban landscapes act to intensify climate change impacts such as flooding and heatwaves (EEA, 2012), they can also have a moderating influence. Green infrastructure is a particular feature of urban areas that performs this function (EEA, 2012; European Commission, 2012). The European Commission (2013: 7) defines green infrastructure as "…a strategically planned network of high quality natural and semi-natural areas with other environmental features". This can encompass, for example, vegetated areas, parks, gardens, wetlands, natural areas, green roofs and trees (EEA, 2012). Green infrastructure is associated with the concept of adaptive capacity. Swart et al. (2012) note that green infrastructure enhances capacity to respond to climate change impacts, including heat stress and flooding, by lowering surrounding air temperatures and providing water storage and infiltration capacity.

Studies on urban parks and green spaces indicate that they have a cooling effect on surrounding areas (Hamada & Ohta, 2010; Spronken-Smith & Oke, 1998). Akbari and Konopacki (2005) demonstrated that widespread tree planting can affect the energy balance of a whole city, highlighting the potential cumulative impact of a city's green infrastructure network on moderating air temperatures. Trees and green spaces also have the potential to reduce flood risk by capturing rainwater, increasing evapotranspiration and raising the infiltration capacity of urban landscapes (Armson, Stringer, & Ennos, 2013; Bartens, Day, Harris, Dove, & Wynn, 2008; Stovin, Jorgensen, & Clayden, 2008). Catchment scale modelling has demonstrated that changing the surface area of green infrastructure cover influences the volume of run-off produced following rainfall events (Carter, Handley, Butlin, & Gill, 2017). Taking these ideas forward in practice, building on work in European and American cities on sustainable urban drainage systems (SuDS) (Zhou, 2014), the concept of 'sponge cities' is taking hold. These approaches are receiving particular interest in China where cities are suffering from flooding and water shortages, and a number of sponge city pilots are underway drawing on government funding. Liu et al. (2017: 473) describe a sponge city as:

> …an urban environment that is devoted to finding ecologically suitable alternatives to transform urban infrastructures into green infrastructures so these could capture, control and reuse precipitation in a useful, ecologically sound way.

It is recognised that adaptive capacity is not static and changes over time (Alberini, Chiabai, & Muehlenbachs, 2006; IPCC, 2007). The connection between green infrastructure and adaptive capacity illustrates this point. As urban areas expand or conversely 'shrink', influenced by multiple local and global drivers, the nature and extent of green infrastructure coverage will also change. For example, green infrastructure may be protected and enhanced by spatial planning policies (Lennon & Scott, 2014), or conversely may be lost due to urban expansion, driven by pressures including population growth and economic development (Angel, Sheppard, & Civco, 2005). These changes can, over time, affect the capacity of cities and urban areas to address climate-related risks, both positively and negatively depending on how ~~the nature of~~ land use changes. However, it is difficult to predict the direction of drivers of urban land use change and, consequently, long-term urban planning exercises are confronted with challenges posed by uncertainty (Balducci, Boelens, Hillier, Nyseth, & Wilkinson, 2011). Scenario-based approaches can be applied in response to the uncertainty that characterises urban dynamics to strengthen understanding of the nature and implications of future urban land use change.

Scenarios have been used extensively across a range of sectors to support the process of bringing a futures perspective into planning and decision-making (Bezold, 2010; European Environment Agency, 2009). It is important to remember that scenarios are not intended to be true representations of alternative futures (Selin, 2005). Scenarios present plausible possible future visions, and are usually formed around a series of 'drivers of change'. Drivers of change incorporated within established scenario processes focus~~ed~~ on different sectors include those concerning demographic, economic, environmental, policy, scientific, social, technological, cultural and values related issues (Nakicenovic et al., 2000; Natural England, 2009; Nelson et al., 2006). Scenarios are often developed in collaboration with stakeholders, and are intended to provoke discussion and support decision-making (EEA, 2009). Scenario outputs can also contribute to modelling exercises. For example, scenarios are developed to create different potential future greenhouse gas emissions trajectories, which subsequently feed into climate models to produce temperature and precipitation projections (IPCC, 2013). Although there is now broad consensus that climate change is occurring and looks set to intensify (IPCC, 2013), the need for scenarios in this context reflects our incomplete knowledge of key climate processes and inability to predict future greenhouse gas emissions trajectories (Dessai & Hulme, 2004).

Several studies have been published that apply scenario-based approaches to look at land use change in the context of urban climate change impacts. Storch and Downes (2011) assessed the implications of different land use and sea level rise scenarios in Ho Chi Minh City. Tong, Sun, Ranatunga, He, and Yang (2012) developed scenarios to look at the relationship between future land use and climate change impacts in the context of urban hydrology and water quality issues. However, examples of studies that apply scenario-based methods in the context of urban land use change and climate change adaptation appear to be lacking. This paper addresses this gap by providing a case study based on Greater Manchester that uses scenarios to develop a long-term perspective of the relationship between land use change, green infrastructure and the capacity of urban areas to adapt to climate change. In doing so, it also responds to the recognised need for further research into the application of land use change models in order to better understand the role of urban land in the context of climate change (Blanco, McCarney, Parnell, Schmidt, & Seto, 2011).

~~3.~~3 Methods

The methods applied within this paper~~ and described within this section~~ are based on a case study focused on Greater Manchester, situated in North West England. Greater Manchester is a post-industrial city-region housing around 2.7 million people, with population growth of around 300,000 by 2035 being planned for by the city-region authorities (GMCA, 2016). Topographically, hills rising to around 500~~ metres~~ m frame the city to the north and east. These upland areas contain the sources of several rivers that flow through the city centre and out via the River Mersey into the Irish Sea to the west. The administrative boundary of Greater Manchester defines the spatial scope of the land use modelling work undertaken within the case study. Detailed land use data was an essential input to the model, and is available at the Greater Manchester scale for different years. Further, as city-region authorities work collaboratively on spatial planning initiatives at this scale, this gives the outcomes of the study greater policy relevance and utility locally. It is acknowledged that some climate change impacts and related biophysical processes operate at larger spatial scales, particularly concerning flooding in the context of river catchments. Flooding is currently Greater Manchester~~'~~'s most prevalent climate-related hazard, with high temperatures and heatwaves (and flooding) projected to become more common over the coming decades (Carter et al., 2015). Accordingly, these two hazards provide the specific focus for this study.

Spatial transition models, which include cellular automata and agent-based models, can enhance climate change adaptation approaches by increasing knowledge of urban growth processes and patterns (Blanco et al., 2011). Metronamica was applied within this study for modelling future land use change across Greater Manchester. Metronamica is a spatial decision support system that uses constrained cellular automata (CCA) to generate dynamic land use change scenarios. CCA dates back to the work of Tobler (1970), who modelled land use change in Detroit using this method. CCA is a cell-based modelling approach in which individual cells are influenced by the behaviour of surrounding cells, generating a dynamic system of change within a constrained land use map. Metronamica has most commonly been used to enhance understanding of the spatial implications of future land use scenarios to inform longer-term planning decisions, and was therefore ideally suited to this study. It has been used by government authorities and research groups to model future land use change in various countries around the world (including the Netherlands, Canada, New Zealand and Nigeria), and at various scales (from continents and countries, to cities) (Barredo, Demichelli, Lavalle, Kasanko, & McCormick, 2004; Hoogeveen, Volkery, Henrichs, & Ribeiro, 2006; Kok & van Delden, 2009; van Vliet, White, & Dragicevic, 2009).

Within this study, the application of Metronamica began with the calibration of the model. The calibration process was based around observing actual land use change in the study area (in this case the Greater Manchester conurbation) over a nine-year period and then calibrating Metronamica to replicate this observed change in land use within the model. Land use maps of Greater Manchester for 1997 and 2006 were used to undertake this task, which were the most up-to-date maps available at the time of the study. An established method based on interpreting aerial photography images was used to create the land use maps (Gill, 2006; Gill et al., 2007). Additional input data related to Greater Manchester, including figures for population and jobs for 1997 and 2006, topographical maps, land use zoning maps and transport network layers, was gathered from publicly available sources and used during the calibration of the Metronamica model.

The Greater Manchester Metronamica case study was structured around grid cells of equal size; 100~~x~~ × 100~~ metres~~ m (or ~~one hectare~~1 ha). Each cell is allocated to one type of land use. Fifteen land use types were actively allocated by Metronamica in the Greater Manchester case, details of which are included in Table 1. This table also includes details of the percentage of the land cover types that are evapotranspiring, which, following Gill (2006), refers to surfaces covered by vegetation and water. Evapotranspiring surfaces are used as an indicator of green infrastructure coverage within this study. The Metronamica model was used to determine whether, at each one-year time step in the model run, the cell will transition to a different land use or persist in its current state. This decision is influenced by four key factors (RIKS, n.d.):

1. Physical suitability, based on the physical characteristics of the location (e.g. slope).
2. Institutional suitability, as determined by spatial restrictions on the allocation of land uses (e.g. zoning regulations).
3. Accessibility, particularly in terms of proximity to transportation networks.

4. Neighbourhood potential, which concerns adjacent land uses and the degree to which a cell is attracted to or repelled by these particular land uses.

~~Table 1:~~Table 1 Descriptions of land use types actively allocated within Metronamica, including the percentage of the land use type that is evapotranspiring (following Gill, 2006).

alt-text: Table 1

Descriptions of land use types actively allocated within Metronamica (following Gill, 2006)			
IF - **improved farmland**: Fields (can contain animals), managed agriculture - 95% evapotranspiring.	**UF** - **unimproved farmland**: Open land with grazing animals - 91% evapotranspiring.	**W** - **woodland**: Continuous tree cover – 98% evapotranspiring.	**TC** - **town centre**: A mixture of retail, offices, and housing - 20% evapotranspiring.
RC - **remnant countryside**: Pockets of countryside surrounded by development, lack management or maintenance, potential for informal recreation - 95% evapotranspiring.	**D + D** - **disused and derelict land**: Variety of former land uses which have become derelict, lack management or maintenance, aspect and colour of ground - 78% evapotranspiring.	**HDR** – **high-density residential**: Terraced housing, town houses, or flatted accommodation, with small or no gardens and yards, and few or no opportunities for planting trees - 31% evapotranspiring.	**M + S** - **manufacturing and storage**: Manufacturing: industrial processes, large buildings, hard-surfaced yards, few locations for trees except around the periphery, site may include regenerated derelict areas - 29% evapotranspiring. Storage: small buildings including warehouses, often with lorries parked outside - 30% evapotranspiring.
IOS - **informal open space**: Grassland and woodland, usually on the edges of towns, can be used for informal recreation, include commons, greens, expanses of mown grass - 94% evapotranspiring.	**O + R** - **office and retail**: Office: blocks of buildings, no industrial activity, business parks, car parks - 45% evapotranspiring. Retail: large shopping centres, commercial streets - 24% evapotranspiring.	**MDR** – **medium-density residential**: Larger terraced houses, semi-detached houses, bungalow estates with large front and back gardens, significant numbers of trees - 50% evapotranspiring.	**S + H** - **schools and hospitals**: Schools: buildings, smaller schools with hard-surfaced yards and few green spaces and trees, larger schools with playing fields - 71% evapotranspiring. Hospitals: often occupy large sites which are heavily planted - 46% evapotranspiring.
FOS - **formal open space**: Designed public open space such as parks, gardens and town squares - 90% evapotranspiring.	**A** - **allotments**: Distinctive rectangular pattern of layout - 87% evapotranspiring.	**LDR** – **low-density residential**: Detached houses, large gardens with lawns and many trees, driveways - 66% evapotranspiring.	

Further details on the Metronamica model and the different elements of the calibration process are available within a dedicated report prepared by the developers of the model (RIKS, n.d.).

Once calibrated, the model provided a platform to analyse the implications of future scenarios for Greater Manchester on land use patterns. Within the Prospective Environmental Analysis of Land Use Development in Europe (PRELUDE) project, led by the European Environment Agency, narrative scenario storylines informed a Metronamica modelling exercise to arrive at different land use futures for Europe (Hoogeveen et al., 2006). This approach, combining future scenarios and land use modelling, was followed within this study.

Two scenarios, developed via a collaborative process with stakeholders from Greater Manchester and the North West region of England, were used as the basis of this modelling work. The first stage in the scenario development process was to identify and prioritise ‘drivers of change’, which are issues with the potential to influence the future growth and development of Greater Manchester. Ten key drivers of change were established as particularly important for the city-region via a literature review of existing scenarios and futures studies to identify cross-cutting themes, eight interviews with local and regional stakeholders working in the public, private and third sectors, and two workshops which involved around 50 people representing public, private and third sector organisations active in and around Greater Manchester. The drivers of change identified via this process were:

1. The nature of technological change
2. The form and function of critical infrastructure
3. Patterns of economic growth
4. The state of the economy
5. The values and consumption patterns of citizens
6. Social dynamics in the city
7. Population and demographic change
8. Climate change – direct impacts and secondary effects

9. Availability and use of natural resources (particularly energy)

10. Governance, regulation and legislation

The ten drivers of change were used as the basis to form two scenarios, developed within two workshops. These involved stakeholders from regional and local organisations~~ that~~ engaged in activities linked to the growth and development of Greater Manchester, including planning authorities, environmental organisations and consultancies. The scenarios were named Upward Spiral and Long Descent, and are reported within a separate document (Carter, 2011). The scenarios offer two distinct and contrasting narratives of how Greater Manchester may develop as a city-region over the coming decades. They are generic in focus rather than concentrating on a particular theme or sector. Upward Spiral offers a vision of growth, prosperity and environmental sustainability. The focus on both economic growth and sustainability that forms the core of this scenario reflects the development of Greater Manchester from both an economic and environmental perspective. The city-region develops and expands, but in a way that remains sensitive to environmental agendas (including climate change), principally guided by spatial planning regulations. In contrast, the Long Descent scenario presents a more challenging future for Greater Manchester. Key themes that characterise the city-region under this scenario include economic and urban decline, limited regulation over the form and location of new development via spatial planning, inequality and environmental degradation.

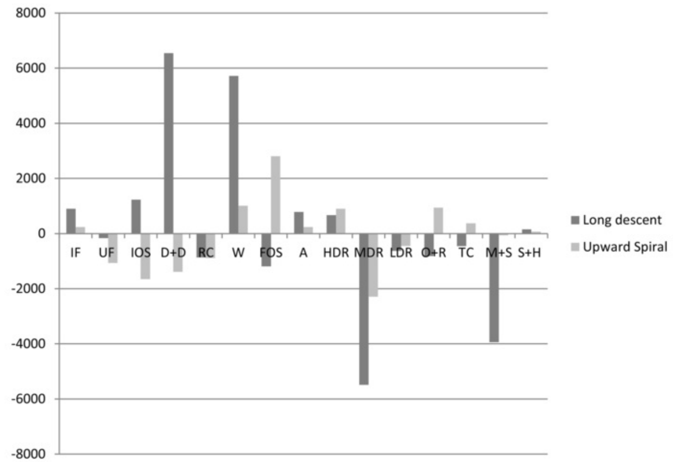
Following the process undertaken in the PRELUDE project, the Upward Spiral and Long Descent scenario storylines were analysed to look for elements connected to land use change and spatial planning frameworks that influence the use and development of land. This resulted in the identification of the principal land use processes to represent within the Metronamica model, via the four components of the model noted above (namely physical and institutional suitability, accessibility and neighbourhood potential), in order to create two future land use scenarios for Greater Manchester. The time period covered by the modelling exercise was 2006 (the baseline from which the modelling started) to 2050. The scenarios are presented and analysed in the following section.

~~4.~~4 Results

The Upward Spiral and Long Descent scenarios underpinned the creation of two future land use scenarios for Greater Manchester, using the Metronamica model. Land use changes observed for each scenario for the period covering 2006~~-~~–2050 are described and analysed within this section. Particular attention is paid to changes in green infrastructure cover, and related implications for adaptive capacity and climate risk are discussed.

~~4.1.~~4.1 The Long Descent scenario

Key land cover changes associated with the Long Descent scenario include a decline in urban land uses, particularly office and retail, and manufacturing and storage. A reduction in area of around 60% is seen for these land uses across Greater Manchester between 2006 and 2050, reflecting the decline in economic activity that characterises this scenario. Urban land cover loss is balanced by increases in non-urban land cover, particularly disused and derelict land and woodlands which grow by 6~~,~~542 and 5~~,~~720 cells respectively between 2006 and 2050 (each cell is 100~~ x ~~ × 100~~ metres~~ m in size, or ~~one hectare~~1 ha). Allotments also expand due to the high price of imported food that is an element of this scenario, with resulting growth in informal urban agriculture. Fig~~ure~~. 1 visualises the land use changes resulting from this scenario.



Key for Figure 1 (see Table 1 for a description of the land use types).			
IF: Improved farmland	**RC:** Remnant countryside	**HDR:** High-density residential	**TC:** Town centre
UF: Unimproved farmland	**W:** Woodland	**MDR:** Medium-density residential	**M+S:** Manufacturing and storage
IOS: Informal open space	**FOS:** Formal open space	**LDR:** Low-density residential	**S+H:** Schools and hospitals
D+D: Disused and derelict land	**A:** Allotments	**O+R:** Office and retail	

~~Figure 1.~~Fig. 1 Change in number of 100~~x~~ × 100 metre cells between 2006 and 2050 for 15 land use types under two scenarios for Greater Manchester.

alt-text: Fig. 1

The Long Descent scenario raises an interesting set of issues in the context of urban adaptive capacity in the face of climate change. This scenario reflects a gradual process of urban decline, and is challenging in terms of socio-economic factors. The land cover changes observed under this scenario represents a shift from land use types that have a lower proportion of evapotranspiring surface (i.e. office and retail, and manufacturing and storage) to those that have a higher proportion of evapotranspiring surface (i.e. disused and derelict land, woodlands and allotments). Table 1 provides details of the proportion of evapotranspiring surface associated with each land use type. Economic decline and the related slowing of development activity result in an increase in the amount of evapotranspiring land cover. This is beneficial in the context of dimensions of urban adaptive capacity linked to green infrastructure, including the provision of functions such as evaporative cooling and rainwater infiltration. This could support the reduction of risks linked to flooding and heatwaves, which are significant climate change hazards in the Greater Manchester context. However, it is acknowledged that ecological succession processes connected to the conversion of urbanised spaces into land cover dominated by green infrastructure can take decades, and remaining underlying substrates will continue to limit rainwater absorption capacity.

~~4.2.~~4.2 The Upward Spiral ~~S~~scenario

Fig~~ure~~. 1 displays Metronamica model outputs showing changes in land cover in Greater Manchester occurring between 2006 and 2050 under the Upward Spiral scenario. With regard to non-urban land uses, planning policies encourage the protection and expansion of landscapes such as woodlands and natural areas. Similarly, land that provides recreation opportunities, including formal open space and allotments, also increases under this scenario. In terms of changes in surface area, formal open space, which increases by 2~~,~~806 cells (each measuring 100~~x~~ × 100~~ metres~~ m, or ~~one hectare~~1 ha), is particularly prominent. The Metronamica model demonstrates that much of the increase in formal open space occurs at the expense of disused and derelict land and informal open space. Essentially, undeveloped open space becomes more intensively managed for recreation purposes. Woodland also grows considerably, adding 1~~,~~010 cells by 2050.

Of the urban land uses, declines in area are seen for medium-density residential (loss of 2~~,~~289 cells) and low-density residential (loss of 446 cells). This reflects the policy of densification that is a feature of this scenario, and the associated development of housing closer to public transport nodes. High-density residential and office and retail increase under this scenario, again driven by the densification policy and also the economic growth dimension of this scenario. These land uses replace informal open space and derelict and disused land, which experience declines in surface area.

When considered from the perspective of green infrastructure, the land cover changes associated with the Upward Spiral scenario have the potential to have a negative impact on the capacity of Greater Manchester to adapt to climate change. The overriding trend within this scenario is towards an increase in urban land cover, especially high-density residential and office and retail, both of which have a relatively low proportion of evapotranspiring land cover (as detailed in Table 1). These changes take place at the expense of land with a relatively high level of evapotranspiring cover, including unimproved farmland, informal open space and remnant countryside. This represents a loss of adaptive capacity functions linked to green infrastructure, and a corresponding increase in the risk associated with climate hazards such as flooding and heatwaves that are projected to increase in frequency and severity in Greater Manchester over the coming decades.

~~4.3.~~4.3 Comparing the adaptive capacity implications of changes to green infrastructure cover under the Upward Spiral and Long Descent scenarios

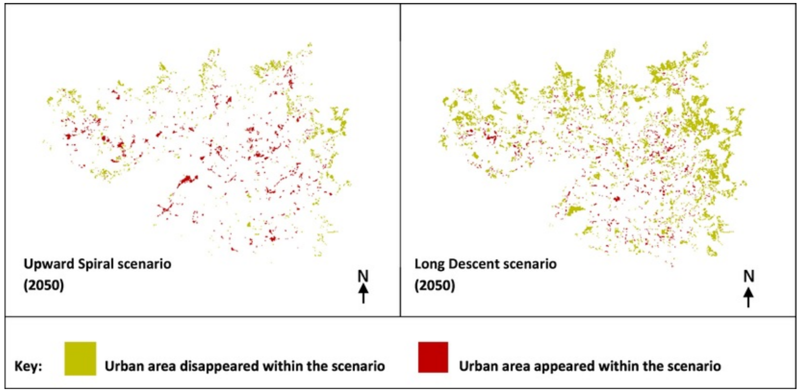
Sections 4.1 and 4.2 assessed land cover changes linked to two contrasting future scenarios for Greater Manchester. The adaptive capacity implications of associated changes in green infrastructure cover have been introduced, and this section provides a comparative assessment of the scenarios in this respect. Table 2 compares the two scenarios against several indicators related to green infrastructure, produced using the Metronamica model. This demonstrates that there is a greater increase in woodland cover (afforestation) within the Long Descent scenario relative to the Upward Spiral scenario. Woodland can support flood risk management by enabling rainwater capture and infiltration, in addition to slowing run-off into watercourses. This is valuable in the context of climate change adaptation given that Greater Manchester is projected to face wetter winters and more incidences of extreme rainfall across the year (Cavan, 2011). Woodland also cools the surrounding air, providing benefits to urban areas such as Greater Manchester, where higher temperatures and more heatwaves are projected for the coming decades (Cavan, 2011). Further, there is also around 10,000~~ hectares~~ha less soil sealing under the Long Descent scenario than the Upward Spiral scenario. This suggests additional flood risk management functionality under the Long Descent scenario relative to the Upward Spiral scenario due to the greater capacity of the urban landscape to absorb rainwater. These indicators highlight that although Upward Spiral is a positive scenario in many respects, the associated loss of green infrastructure cover has the potential to be detrimental to the adaptive capacity of Greater Manchester, and to a greater degree than under the Long Descent scenario.

~~Table 2.~~Table 2 Comparison of two scenarios for Greater Manchester against a series of indicators related to green infrastructure cover.

alt-text: Table 2

Indicator	Upward Spiral scenario	Long Descent scenario
Area of soil sealing by 2050 (100~~x~~ × 100 metre cells)	58,664	48,690
Urban area disappeared between 2006~~-~~ and 2050 (100~~x~~ × 100 metre cells)	3~~,~~120	12,496
Urban area appeared between 2006~~-~~ and 2050 (100~~x~~ × 100 metre cells)	2~~,~~591	1~~,~~993
Deforestation between 2006~~-~~ and 2050 (100~~x~~ × 100 metre cells)	458	97
Afforestation between 2006~~-~~ and 2050 (100~~x~~ × 100 metre cells)	1~~,~~468	5~~,~~817

Fig~~ure~~. 2 visualises changes in urban area associated with each scenario on maps of Greater Manchester. Considered from the perspective of broad patterns rather than specific spatial details, it is apparent that where new urban land emerges, this tends to cluster in the Upward Spiral scenario. Conversely, new urban land is more widely dispersed across the conurbation under the Long Descent scenario. Fig~~ure~~. 2 also indicates that where urban land cover is lost, this tends to occur in the urban fringe within the Upward Spiral scenario, reflecting the densification policy present within this scenario. Within the Long Descent scenario, spatial planning policies are less comprehensive and effective, and consequently Fig~~ure~~. 2 reveals that the loss of urban land is widespread and unstructured. However, under both scenarios, the northern and eastern fringes of the conurbation do see notable losses of urban land. In Greater Manchester these hinterland areas are upland landscapes characterised by urbanised areas, open moorlands and tributaries of the main rivers that flow through the urban centres of the conurbation. Over time, the conversion of urban land to non-urban land in these areas may have positive flood risk management benefits connected to slowing the run-off of water into rivers that flow downstream into the conurbation~~'~~'s more heavily urbanised areas. This illustrates the need to be aware of local geography and topography when assessing the implications of future land cover scenarios such as those produced by Metronamica.



~~Figure 2.~~Fig. 2 Change in urban land cover (2006~~-~~–2050) under two scenarios for Greater Manchester.

alt-text: Fig. 2

Of course, protecting and enhancing green infrastructure cover is only one aspect of maintaining and building adaptive capacity, which extends across a wide range of themes (Alberini et al., 2006; Smit & Wandel, 2006). Many elements of the Long Descent scenario are detrimental to adaptive capacity from a broader perspective, including a lack of social cohesion and the existence of governance structures that pay little attention to climate change, whilst the opposite is true for the Upward Spiral scenario. Nevertheless, this comparative assessment emphasises that contrasting future scenarios for Greater Manchester have differing effects on adaptive capacity when considered from the perspective of green infrastructure cover, some of which may initially seem counter-intuitive.

~~5.~~5 Discussion

The two scenarios for Greater Manchester presented within this paper resonate with broader patterns of expansion and shrinkage that are playing out across urban areas globally, and also within individual countries and regions. People and capital move to thriving cities for work and productive investment. Cities currently experiencing the fastest population growth rates are concentrated in Africa, Asia and Latin America (United Nations, 2014), although there is also a network of cities in the developed world that continue to grow and dominate their surrounding regions and globalisation processes more generally (Sassen, 2001). The Metronamica model outputs for the Upward Spiral scenario raises the prospect of existing green infrastructure in Greater Manchester being pressured by new development. This highlights that cities experiencing economic growth and associated increases in population are in danger of losing green infrastructure resources that can support adaptation to climate change and the achievement of broader quality of life objectives. In response, proactive strategies to conserve and enhance green infrastructure are needed to moderate and offset the impacts of urban infill and expansion on this resource. Without such strategies, the risk is that green infrastructure, and therefore adaptive capacity, will be lost. It is encouraging that an increasing number of cities are taking positive steps in this direction, with specific strategies including developing zoning policies to protect existing resources and providing incentives to developers to incorporate green infrastructure within their schemes (Kazmierczak & Carter, 2010). The findings of this study place further emphasis on the need to progress urban green infrastructure strategies and investments in cities that are pursuing expansionary growth strategies.

The processes that increase the dominance of certain cities benefiting from comparative advantages can contribute to the corresponding deindustrialisation and relative decline of other cities (Hall, 1993; Pike et al., 2016), which can find themselves "…'unplugged' from international engines of growth" (Martinez-Fernandez et al., 2012: 220). The notion of shrinking cities has become more widely recognised over recent decades as a global process, although it is not a new phenomenon and dates back to the Chicago School of urban sociology and theories of cyclical patterns of growth and decline (Martinez-Fernandez et al., 2012). Shrinkage in this context is multidimensional process connected to broader drivers including demographic change, deindustrialisation and globalisation (Hall, 1993; Martinez-Fernandez et al., 2012; McKinsey and Company, 2016). Shrinking cities have been defined as "…places characterised by decline in different fields, such as business activities, revenues or population numbers" (Dietersdorfer et al., 2012: 9). Shrinking cities also harbour high levels of vacant properties and land parcels (Burkholder, 2012; Schilling & Logan, 2008). Shrinking cities have been identified as a phenomenon that is particularly associated with North America, Europe and Japan, and are projected to become more widespread in these areas. Between 2015 and 2025, 17% of large cities in the world~~'~~'s developed regions are projected to experience population decline (McKinsey and Company, 2016).

It is apparent that shrinking cities share parallels with the Long Descent scenario developed within this study, which features characteristics including economic decline and the associated conversion of urban land uses connected to sectors including manufacturing, storage, office and retail into disused and derelict land and woodlands. The analysis of the Long Descent scenario for Greater Manchester illustrates how urban processes linked to shrinkage and decline can in turn increase urban green infrastructure cover. This may be viewed as an opportunity in terms of building adaptive capacity, although it is recognised that other socio-economic dimensions of urban shrinkage and decline may hinder the achievement of this goal. Given the projections for an increase in the number of shrinking cities, and that urban shrinkage is seen as a structural rather than temporary phenomenon (Martinez-Fernandez et al., 2012), strategies are needed build capacity to adapt to climate change in this context. There examples of shrinking cities that are working to address related challenges by enhancing green infrastructure cover, particularly in North America and Eastern Germany (Burkholder, 2012; Hollander et al 2009, Schetke & Haase, 2008; Schilling & Logan, 2008; Wiechmann & Pallagst, 2012). Related strategies being employed in these cities include land banking to secure spaces to implement green infrastructure projects, promoting the varied use of vacant sites (e.g. for recreation and urban agriculture) and developing approaches to empower local communities to adopt and manage green infrastructure sites. In some shrinking cities in the US, including Philadelphia and Youngstown, such approaches are delivering benefits linked to climate change adaptation such as improved storm water management (Schilling & Logan, 2008).

Two key trends facing cities over the coming decades are relevant to the discussion of the research findings presented within this paper. The first is that observed processes of growth and shrinkage facing the global landscape of cities look set to continue. The second is that projections point towards an intensification of urban climate change impacts (IPCC, 2014). It is also notable that green infrastructure is increasingly recognised as an important element of maintaining and building the adaptive capacity of urban areas. The scenarios for the future growth and development of Greater Manchester bring together each of these themes, and provide illustrative examples of how urban growth and shrinkage processes could impact on adaptive capacity in cities from the perspective of green infrastructure coverage. Ultimately, strategic green infrastructure planning is needed to support climate change adaptation in expanding and shrinking cities. This should ideally be supported by Geographical Information Systems (GIS) analysis to identify, spatially, opportunities for green infrastructure conservation, intervention and investment. Here, it is also necessary to consider other factors. Patterns of climate change vulnerability and risk are uneven in urban areas (Carter et al., 2015). Green infrastructure siting decisions can help to moderate this inequality and encourage associated adaptation benefits to be shared spatially and amongst different communities where vulnerability and risk are high. ~~This~~A strategic and spatially informed approach such as this ~~has the potential to~~ can deliver broader benefits in expanding and shrinking urban contexts. With the impacts of climate change projected to become increasingly severe, the potential exists for ‘well adapted’ shrinking cities housing extensive green infrastructure resources to become areas of future opportunity. Similarly, in an era of ~~intense~~ global rivalry between cities, it is conceivable that capacity to adapt to climate change will emerge more strongly as a factor influencing prospects for future growth and prosperity. ~~t~~Those cities that develop strategies to grow and expand in ~~a~~ ways that moderate~~s~~ climate change risks by conserving and enhancing urban green infrastructure ~~may~~could gain a ~~significant~~ competitive advantage.

Uncited references

~~Forest Research, 2010~~ (Delete Forest Research 2010 from the paper)

~~Getter and Rowe, 2006~~ (Delete Getter and Rowe from the paper)

~~Pérez-Urrestarazu et al., 2016~~ (Delete Perez-Urrestarazu et al from the paper)

~~Rindfuss et al., 2008~~ (Delete Ridfuss et al from the paper)

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Highlights **(I have included 4 new highlights in the instruction at the end of this section.)**

- ~~Green infrastructure can enhance the capacity of urban areas to adapt to climate change by providing functions such as evaporative cooling and rainwater infiltration.~~
- ~~Land use change modifies green infrastructure cover and in turn influences the capacity of urban areas to adapt to climate change.~~
- ~~A case study based on Greater Manchester in Northwest England provides insights into the relationship between different future land cover scenarios, green infrastructure and capacity to adapt to climate change.~~
- ~~Regardless of the land cover future facing urban areas, strategies are needed to protect and enhance urban green infrastructure in order to maintain and build adaptive capacity and moderate climate-related risks.~~ (Green infrastructure supports climate change adaptation via functions such as evaporative cooling and rainwater infiltration.

  Urban land use change modifies green infrastructure cover and in turn influences capacity to adapt to climate change.

  This paper explores the relationship between future land cover scenarios, green infrastructure and adaptive capacity.

  Green infrastructure should be protected and enhanced to build adaptive capacity and moderate climate-related risks.)

Queries and Answers

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Please check the presentation of Tables 1 and 2 if correct.

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Answer: Green infrastructure supports climate change adaptation via functions such as evaporative cooling and rainwater infiltration.
Urban land use change modifies green infrastructure cover and in turn influences capacity to adapt to climate change.
This paper explores the relationship between future land cover scenarios, green infrastructure and adaptive capacity.
Green infrastructure should be protected and enhanced to build adaptive capacity and moderate climate-related risks.

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Uncited references: This section comprises references that occur in the reference list but not in the body of the text. Please position each reference in the text or, alternatively, delete it. Thank you.

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