Adapting Cities for Climate Change: The Role of the Green Infrastructure

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The urban environment has distinctive biophysical features in relation to surrounding rural areas. These include an altered energy exchange creating an urban heat island, and changes to hydrology such as increased surface runoff of rainwater. Such changes are, in part, a result of the altered surface cover of the urban area. For example less vegetated surfaces lead to a decrease in evaporative cooling, whilst an increase in surface sealing results in increased surface runoff. Climate change will amplify these distinctive features. This paper explores the important role that the green infrastructure, i.e. the greenspace network, of a city can play in adapting for climate change. It uses the conurbation of Greater Manchester as a case study site. The paper presents output from energy exchange and hydrological models showing surface temperature and surface runoff in relation to the green infrastructure under current and future climate scenarios. The implications for an adaptation strategy to climate change in the urban environment are discussed.

Introduction

Much of the emphasis in planning for climate change is, quite properly, focused on reducing or mitigating greenhouse gas emissions. Present day emissions will impact on the severity of climate change in future years (Hulme *et al*., 2002). However, climate change is already with us. The World Wide Fund for Nature, for example, has recently drawn attention to the significant warming of capital cities across Europe (WWF, 2005). Due to the long shelf-life of carbon dioxide in the atmosphere, much of the climate change over the next 30 to 40 years has already been determined by historic emissions (Hulme *et al*., 2002). Thus, there is a need to prepare for climate change that will occur whatever the trajectory of future greenhouse gas emissions.

With this in mind the UK Engineering and Physical Sciences Research Council (EPSRC) and the UK Climate Impacts Programme (UKCIP) have established a research programme into Building Knowledge for a Changing Climate (BKCC). One project within the BKCC programme, Adaptation Strategies for Climate Change in the Urban Environment (ASCCUE), is developing ways of preparing for climate change through strategic planning and urban design. One important facet of ASCCUE, which is the subject of this paper, is to explore the potential of urban greenspace in adapting cities to climate change.

In 1991, 90 per cent of people in Great Britain lived in urban areas (Denham and White, 1998) and it is here that climate change impacts will be felt. Urban areas have distinctive biophysical features in comparison with surrounding rural areas (Bridgman *et al*., 1995). For example, energy exchanges are modified to create an urban heat island, where air temperatures may be several degrees warmer than in the countryside (Wilby, 2003; Graves *et al.*, 2001). The magnitude of the urban heat island effect varies in time and space as a result of meteorological, locational and urban characteristics (Oke, 1987). Hydrological processes are also altered such that there is an increase in the rate and volume of surface runoff of rainwater (Mansell, 2003; Whitford *et al.*, 2001).

Such biophysical changes are, in part, a result of the altered surface cover of the urban area (Whitford *et al.*, 2001). Urbanization replaces vegetated surfaces, which provide shading, evaporative cooling, and rainwater interception, storage and infiltration functions, with impervious built surfaces. However, urban greenspaces provide areas within the built environment where such processes can take place (Whitford *et al.*, 2001). These ecosystem services (Daily, 1997) provided by urban greenspace are often overlooked and undervalued. For example, trees are felled for the perceived threat they pose near highways and buildings (Biddle, 1998), infill development takes place on former gardens, front gardens are paved over to provide parking spaces for cars, and biodiverse urban 'wasteland' is earmarked for redevelopment (e.g. Duckworth, 2005; GLA, 2005; Pauliet *et al.*, 2005).

In a changing climate the functionality provided by urban greenspace becomes increasingly important. In the UK, climate change scenarios (UKCIP02) suggest average annual temperatures may increase by between 1°C and 5°C by the 2080s, with summer temperatures expected to increase more than winter temperatures. There will also be a change in the seasonality of precipitation, with winters up to 30 per cent wetter by the 2080s and summers up to 50 per cent drier. These figures are dependent on both the region and emissions scenario (Hulme *et al.*, 2002). Precipitation intensity also increases, especially in winter and the number of very hot days increases, especially in summer and autumn (Hulme *et al.*, 2002). It should be noted that these climate change scenarios do not take urban surfaces into account. There is likely to be significant urban warming over and above that expected for rural areas (Wilby and Perry, 2006; Wilby, 2003).

Climate change will impact on the urban environment. These impacts are felt by both people and the built infrastructure. For example, it is estimated that the European summer heat wave in 2003 claimed 35,000 lives (Larsen, 2003). Incidents of flooding also result in both physical and psychological illnesses (e.g. Reacher *et al.*, 2004; Baxter *et al.*, 2002; Shackley *et al.*, 2001). In addition, buildings are vulnerable to flooding depending on their location (Graves and Phillipson, 2000).

The biophysical features of greenspace in urban areas, through the provision of cooler microclimates and reduction of surface water runoff, therefore offer potential to help adapt cities for climate change. However, little is known about the quantity and quality of greenspace required. The green infrastructure is 'an interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations' (Benedict and McMahon, 2002, p. 12). The green infrastructure should operate at all spatial scales from urban centres to the surrounding countryside (URBED, 2004).

The aim of this paper is to explore the potential of green infrastructure in adapting cities for climate change. This will be achieved through a characterization of the case study site, and quantifying its environmental functions under both current and future climate scenarios, as well as with differing patterns of green cover.

Case Study Site

Greater Manchester, selected as the case study site, is representative of a large conurbation (population 2.5 million) in Britain and Northern Europe. The Metropolitan County of Greater Manchester, located in north-west England, is administered by ten local authorities: Bolton, Bury, Manchester, Oldham, Rochdale, Salford, Stockport, Tameside, Trafford, and Wigan. There is some coordination at the conurbation level through the Association of Greater Manchester Authorities, but planning powers at the larger scale are vested in the North West Regional Assembly (NWRA). The NWRA prepares a Regional Spatial Strategy (NWRA, 2006), which is the broad planning framework for the region, whilst the municipalities each prepare a Local Development Framework which provides a more detailed template for development.

Greater Manchester covers an area of approximately 1300 km^2 and has developed on a river basin flanked by the Pennine hills. The altitudinal range is between 10 m and 540 m above sea level. Greater Manchester offers sufficient size for full expression of urban environmental character, contrasting soil types, a range of neighbourhood and land-use types (including restructuring and urban extension areas with substantial scope for climate change adaptation), as well as a range of built forms.

Manchester was one of the world's first industrial cities and the end of that era was marked by extensive dereliction and abandoned transport infrastructure. During the past two decades there has been a change in the fortune of the conurbation with large-scale urban regeneration projects transforming land, water and buildings to new uses. Urban expansion is restricted by Green Belt designation and new development is focused on previously developed, brownfield land. There is also pressure for infill development in lower density residential areas, especially in south Manchester.

Urban Characterization

The first stage of the research was to characterize the urban environment. This involved the mapping of urban morphology types (UMTs) (LUC, 1993) followed by a surface cover analysis. The UMTs effectively serve as integrating spatial units linking human activities and natural processes. The assumption is that UMTs have characteristic physical features and are distinctive according to the human activities that they accommodate (i.e. land uses). Greater Manchester was stratified into 29 distinctive UMTs,

Table 1. Primary and detailed UMT categories.

Primary UMT category	*Detailed UMT categories*
Farmland	Improved farmland, unimproved farmland
Woodland	Woodland
Minerals	Mineral workings and quarries
Recreation and leisure	Formal recreation, formal open space, informal open space, allotments
Transport	Major roads, airports, rail, river and canal
Utilities and infrastructure	Energy production and distribution, water storage and treatment, refuse disposal, cemeteries and crematoria
Residential	High-density residential, medium-density residential, low-density residential
Community services	Schools, hospitals
Retail	Retail, town centre
Industry and business	Manufacturing, offices, distribution and storage
Previously developed land	Disused and derelict land
Defence	Defence
Unused land	Remnant countryside

digitized in ArcView GIS from 1997 aerial photographs (resolution: 0.25 m, source: Cities Revealed). These were grouped into 12 primary UMT categories (table 1).

The primary UMT map for Greater Manchester (figure 1) shows the locations of the various town centres, grouped under the primary UMT category of retail, in Greater Manchester. These are largely surrounded by residential areas. Higher-density residential areas are typically located closer to the town centres. Trafford Park, a major industrial and retail area, can be seen to the west of Manchester city centre. The main transport infrastructure, including Manchester airport in the south and Manchester ship canal to the west, are clearly visible. Farmland surrounds the urban core and in certain instances extends into the urban areas. Towards the south of the conurbation the open land of the Mersey valley forms a greenspace corridor intersecting the mainly residential areas. Some 506 km^2, or just under 40 per cent, of Greater Manchester is farmland, with the remaining 60 per cent (793 km^2) representing the ‘urbanized’ area. Residential areas account for just under half of the urbanized area, or 29 per cent of Greater Manchester, and can thus be viewed from a landscape ecology perspective as the ‘matrix’ – representing the dominant landscape category in the urban mosaic (Forman and Godron, 1986).

Whilst the UMT categories provide an initial indication of where patches of green may be expected, e.g. in formal and informal open spaces, and where green corridors may be found, e.g. alongside roads, railways, rivers and canals, they do not reveal the extent of green cover within the built matrix of the conurbation. Thus, the surface cover of each of the 29 UMT categories was then estimated by aerial photograph interpretation of random points (Akbari *et al.*, 2003). This is very important as the surface cover affects

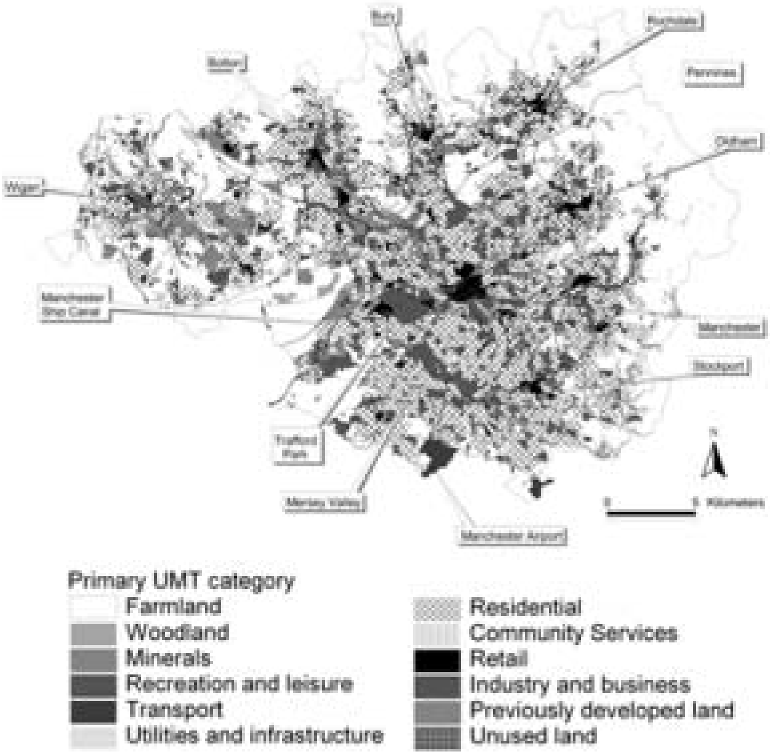

Figure 1. Primary Urban Morphology Type map of Greater Manchester.

the environmental performance of the conurbation (Pauliet *et al*., 2005; Nowak *et al*., 2001; Whitford *et al*., 2001; Pauliet and Duhme, 2000). Nine surface cover types were used: building, other impervious, tree, shrub, mown grass, rough grass, cultivated, water, and bare soil/ gravel.

The results indicate that on average 72 per cent of Greater Manchester, or 59 per cent of the 'urbanized' area, consists of evapotranspiring (i.e. vegetated and water) surfaces (figure 2). All the UMT categories have, on average, more than 20 per cent evapotranspiring surfaces. However, there is considerable variation across the UMTs. Town centres have the lowest evapotranspiring cover of 20 per cent compared to woodlands with the highest cover of 98 per cent. In general, the proportion of tree cover is fairly low, covering on average 12 per cent over Greater Manchester and 16 per cent in 'urbanized' Greater Manchester. Whilst the woodland UMT category has 70 per cent trees, all other UMTs have below 30 per cent tree cover. Town centres have a tree cover of 5 per cent.

Particular attention must be given to the surface cover in residential areas, as these cover almost half of 'urbanized' Greater Manchester and therefore have a great impact on the environmental performance of the conurbation. Approximately 40 per cent of all the evapotranspiring surfaces in 'urbanized' Greater Manchester occur in residential areas, with medium-density residential areas accounting for the majority of such surfaces. The three types of residential area have different surface covers from each other (figure 3). In high-density residential areas built surfaces (i.e. building and other

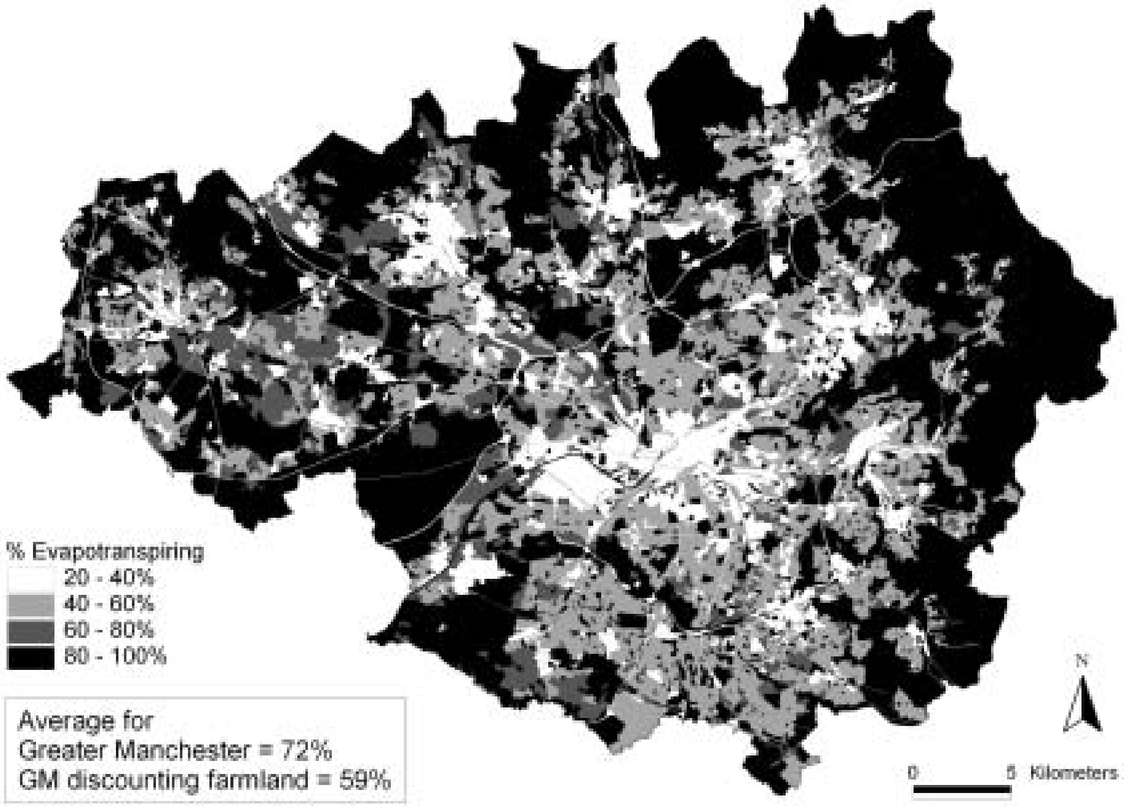

Figure 2. Proportion of evapotranspiring (i.e. vegetated and water) surfaces in Greater Manchester.

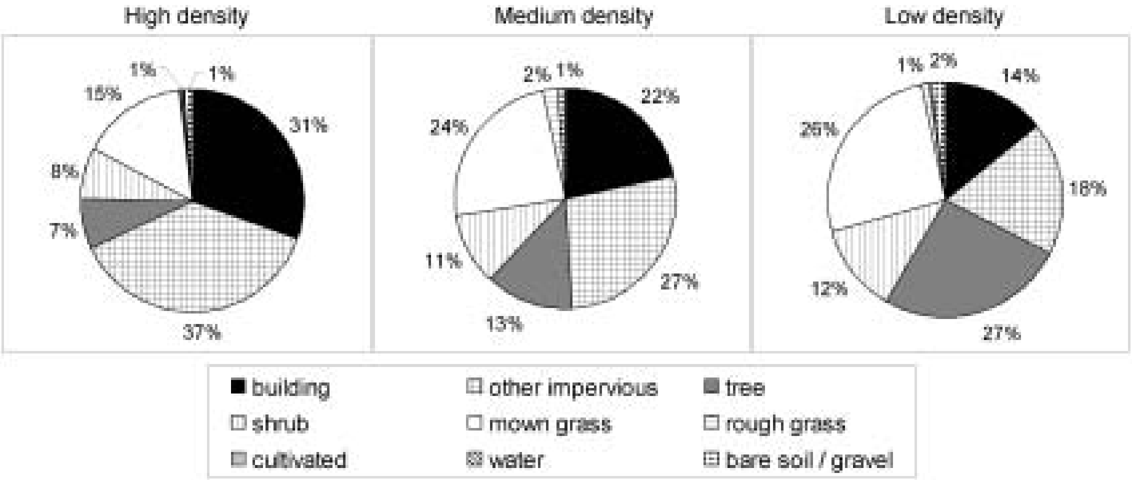

Figure 3. Proportional surface cover in high-, medium- and low-density residential UMTs.

impervious surfaces) cover about two-thirds of the area, compared to about half in medium-density areas and one-third in low-density areas. Tree cover is 26 per cent in low-density areas, 13 per cent in medium-density areas, and 7 per cent in high-density areas.

Quantifying the Environmental Functions

The UMTs, with their distinctive surface covers, formed one of the inputs into energy exchange and surface runoff models (Whitford *et al.*, 2001). The energy exchange model has maximum surface temperature as its output and is based on an energy balance equation (Whitford *et al.*, 2001; Tso *et al.*, 1990, 1991). The warming of the urban environment in summer is an important issue because of its implications for human comfort and well being (e.g. Svensson and Eliasson, 2002; Eliasson, 2000). Whilst air temperature provides a simple estimator of human thermal comfort, it is less reliable outdoors owing to the variability of other factors such as humidity, radiation, wind, and precipitation (Brown and Gillespie, 1995). In practice, the mean radiant temperature, which in essence is a measure of the combined effect of surface temperatures within a space, is a significant factor in determining human comfort, especially on hot days with little wind (Matzarakis *et al.*, 1999). Whitford *et al.* (2001) therefore considered surface temperature to be an effective indicator for energy exchange in the urban environment. As well as requiring input of the proportional area covered by built and evapotranspiring (i.e. all vegetation and water) surfaces, the model also requires a building mass per unit of land, and various meteorological parameters including air temperature.

The surface runoff model uses the curve number approach of the US Soil Conservation Service (Whitford *et al.*, 2001; USDA Natural Resources Conservation Service, 1986). Again, surface cover is required as an input along with precipitation, antecedent moisture conditions, and hydrologic soil type.

The models were run for the baseline 1961–1990 climate, as well as for the UKCIP02 Low and High emissions scenarios for the 2020s, 2050s, and 2080s (Hulme *et al.*, 2002). Results presented here are for the 1961–1990 baseline and the 2080s Low and High emissions scenarios. Temperature and precipitation inputs were calculated for the different time periods and emissions scenarios using daily time series output from a weather generator for Ringway (Manchester Airport) (BETWIXT, 2005; Watts *et al*., 2004*a*). The energy exchange model used the 98th percentile average daily summer temperature for its input, or the average temperature occurring on approximately two days per summer. The surface runoff model used the 99th percentile winter daily precipitation as its input, a precipitation event that occurs approximately once per winter. The 99th percentile daily winter precipitation is 18 mm for 1961–1990, 25 mm for the 2080s Low, and 28 mm for the 2080s High. Results of the surface runoff model presented here are for normal antecedent moisture conditions. However, analysis of the weather generator output suggests that antecedent moisture conditions in winter become wetter with climate change.

Model runs were completed for the UMT categories with their current form, i.e. using proportional surface covers from the urban characterization, as well as for a series of ‘development scenarios’ exploring the impact on environmental functionality of adding and taking away green cover in key areas in the conurbation. The ‘development scenarios’ were intended both to help understand the effects of current development trends (Duckworth, 2005; Pauleit *et al*., 2005), as well as to explore the potential of greening to help adapt urban areas to climate change. They included: residential and town centres plus or minus 10 per cent green or tree cover; greening roofs in selected UMTs; high-density residential development on previously developed land; increasing tree cover by 10–60 per cent on previously developed land; residential development on improved farmland; and permeable paving in selected UMTs. In addition, for the energy exchange model, runs were completed where grass was excluded from the evapotranspiring proportion. This was intended to give some indication of the impact of a drought, when the water supply is limited and plants evapotranspire less, and hence their cooling effect is lost. Grass may be the first type of vegetation in which this happens due to its shallow rooting depth.

Energy Exchange Model

The maximum surface temperature is very dependent on the proportion of green cover (figure 4). This will become increasingly important in the future. Currently the maximum surface temperature of woodlands, the

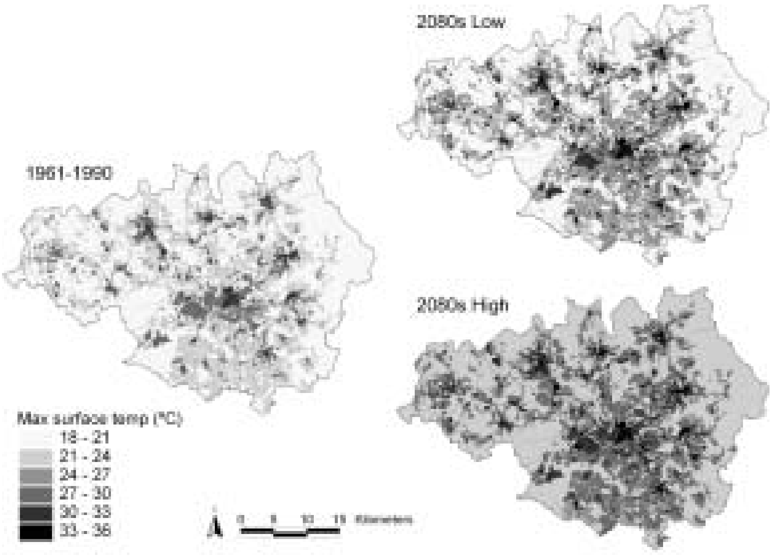

Figure 4. Maximum surface temperature in Greater Manchester for the 98th percentile summer day in 1961–1990 and the 2080s Low and High emissions scenarios.

least built up UMT, is 18.4°C, 12.8°C cooler than that of town centres, the most built up UMT, at 31.2°C. The maximum surface temperatures are 19.9°C in woodlands and 33.2°C in town centres by the 2080s Low and 21.6°C and 35.5°C by the 2080s High. Thus, by the 2080s there are increases in maximum surface temperature of between 1.5°C and 3.2°C in woodlands and 2°C to 4.3°C in town centres, depending on the emissions scenario. The difference in temperatures between these extreme UMTs also increases to 13.9°C by the 2080s High. In high-density residential areas, with an evaporating cover of 31 per cent, maximum surface temperatures increase by 1.7°C and 3.7°C by the 2080s, depending on emissions scenario; in low-density areas, with an evaporating cover of 66 per cent, the increase is 1.4°C to 3.1°C. The temperature difference between these residential UMTs is 6.2°C in 1961–1990, and 6.5°C to 6.8°C by the 2080s, depending on the emissions scenario.

Adding 10 per cent green cover to areas with little green, such as the town centre and high-density residential UMTs keeps maximum surface temperatures at or below the 1961–1990 baseline temperatures up to, but not including, the 2080s High emissions scenario (figures 5 and 6). In high-density residential areas, for example, maximum surface temperatures in 1961–1990 with current form are 27.9°C. Adding 10 per cent green cover decreases maximum surface temperatures by 2.2°C in 1961–1990, and 2.4°C to 2.5°C by the 2080s Low and High emissions scenarios, respectively. Thus, maximum surface temperatures decrease by 0.7°C by the 2080s Low and increase by 1.2°C by the 2080s High, in comparison to the 1961–1990 current form case. This is compared to temperature increases of 1.7°C to 3.7°C by the 2080s Low and High if no change was made to surface cover. On the other hand, if 10 per cent green cover is removed maximum surface temperatures by the 2080s High emissions scenario are 7°C and 8.2°C warmer in high-density residential and town centres, respectively, compared to the 1961–1990 current form case (figures 5 and 6).

Adding green roofs to all buildings can

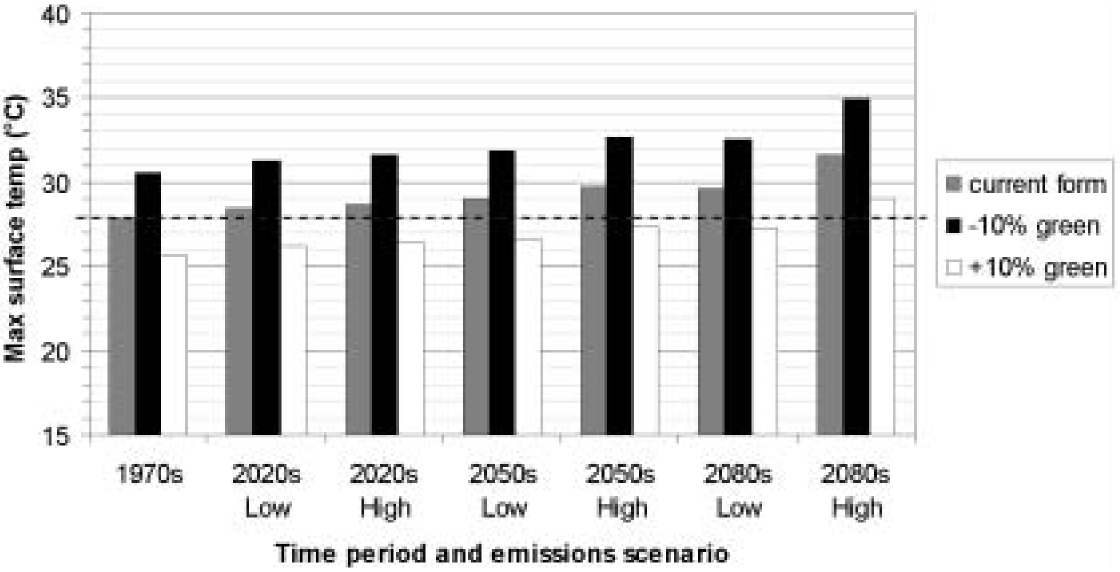

Figure 5. Maximum surface temperature for the 98th percentile summer day in high-density residential areas, with current form and when 10 per cent green cover is added or removed. Dashed line shows the temperature for the 1961–1990 current form case.

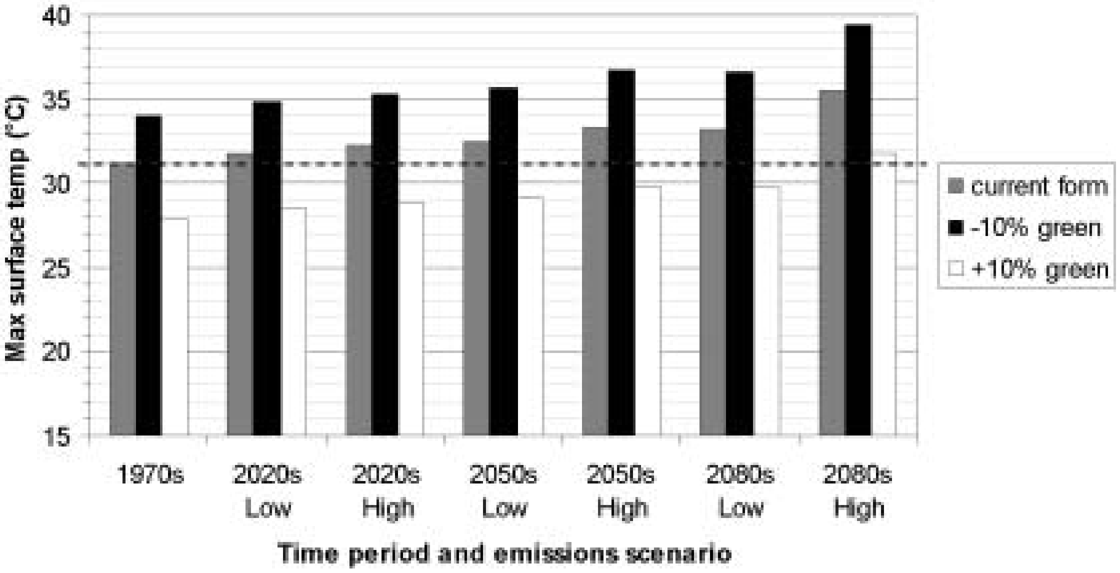

Figure 6. Maximum surface temperature for the 98th percentile summer day in town centres, with current form and when 10 per cent green cover is added or removed. Dashed line shows the temperature for the 1961–1990 current form case.

have a dramatic effect on maximum surface temperatures, keeping temperatures below the 1961–1990 current form case for all time periods and emissions scenarios (figure 7). Roof greening makes the biggest difference in the UMTs where the building proportion is high and the evaporating fraction is low. Thus, the largest difference was made in the town centres followed by manufacturing, high-density residential, distribution and storage, and retail. The difference made by the roof greening becomes greater with the

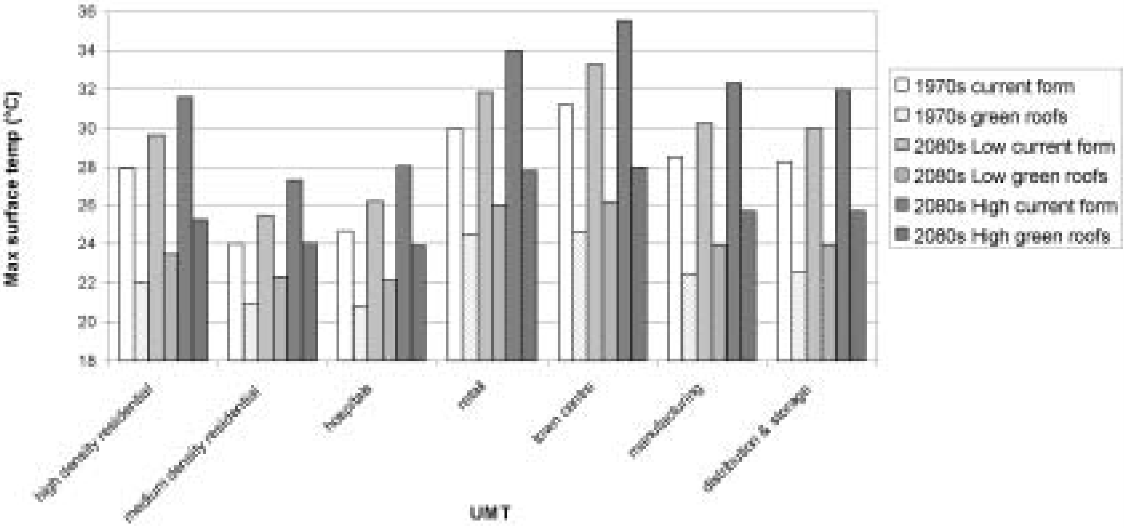

Figure 7. Maximum surface temperature for the 98th percentile summer day in selected UMTs, with current form and when all roofs are greened.

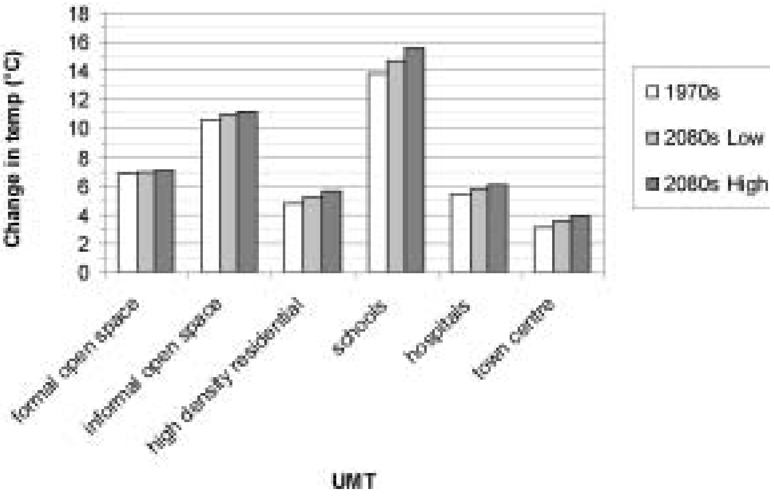

Figure 8. Increase in maximum surface temperature for selected UMTs for the 98th percentile summer day when grass dries out and stops evapotranspiring.

time period and emissions scenario. For example, in 1961–1990, greening roofs results in maximum surface temperatures of 24.6°C in town centres, a decrease of 6.6°C compared to the current form case of 31.2°C. By the 2080s High, greening roofs in town centres results in temperatures of 28°C, 7.6°C less than if roofs are not greened and 3.3°C less than the 1961–1990 current form case.

In contrast, when grass dries and stops evapotranspiring, rivers and canals become the coolest UMT, with maximum surface temperatures of 19.8°C in 1961–1990 and 22.9°C by the 2080s High, followed by woodlands. The UMTs experiencing the biggest change in maximum surface temperature when grass dries out are those where it forms a large proportion of the evaporating fraction (figure 8). For example, in schools which often have large playing fields, the

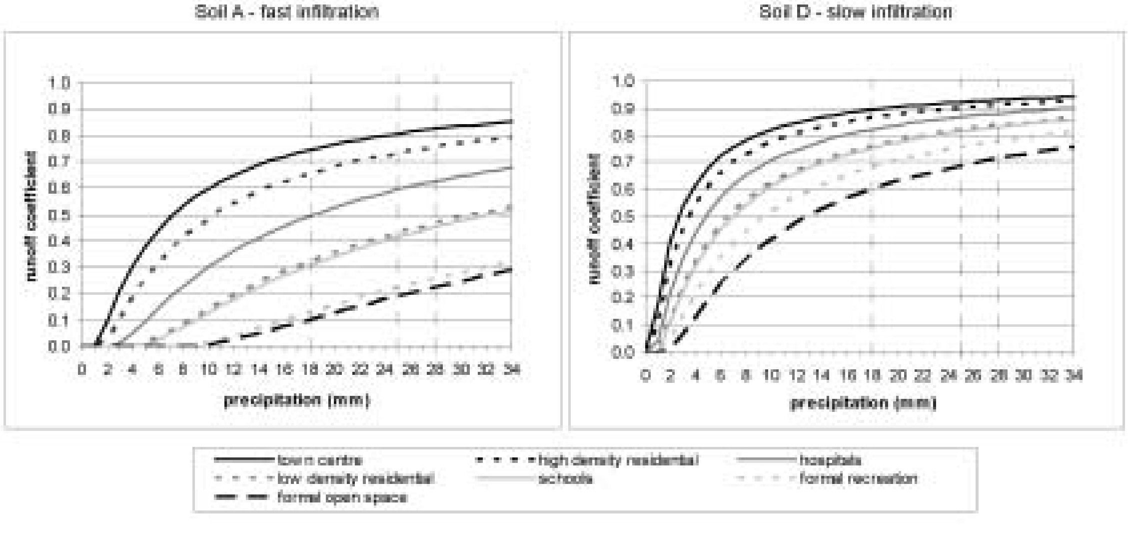

Figure 9. Runoff coefficients for selected UMTs under normal antecedent moisture conditions on a fast and slow infiltrating soil. Vertical dashed lines show the 99th percentile daily winter precipitation for 1961–1990 (18 mm), the 2080s Low (25 mm), and the 2080s High (28 mm).

maximum surface temperature increases by 13.8°C in 1961–1990 and 15.6°C by the 2080s High.

Surface Runoff Model

In general, the more built up a UMT category is the more surface runoff there will be. Additionally, soil type is very important (figure 9). Faster infiltrating soils, such as sandy soils, have lower runoff coefficients than slower infiltrating soils, such as clays. The runoff coefficients display the largest range on high infiltration soils and the smallest range on low infiltration soils. For example, for an 18 mm precipitation event on sandy soil, low-density residential UMTs will have 32 per cent runoff compared with 74 per cent from the more built up town centres, which have the highest runoff coefficients of all the UMTs. On a clay soil this changes to 76 per cent and 90 per cent respectively, much higher values and with a smaller difference between them. Thus, surface sealing has a more significant impact on runoff on a sandy soil with a high infiltration rate than on a clay soil with a low infiltration rate.

With the increasing precipitation expected by the 2080s there will be increased surface runoff (figure 10). Not only will there be higher precipitation but a larger percentage of the precipitation will contribute to surface runoff. The total runoff over Greater Manchester for an 18 mm rainfall event, the 99th percentile winter daily precipitation in 1961–1990, is 13.8 million m^3. Yet for the 28 mm rainfall event, expected by the 2080s High, which has 55.6 per cent more rain

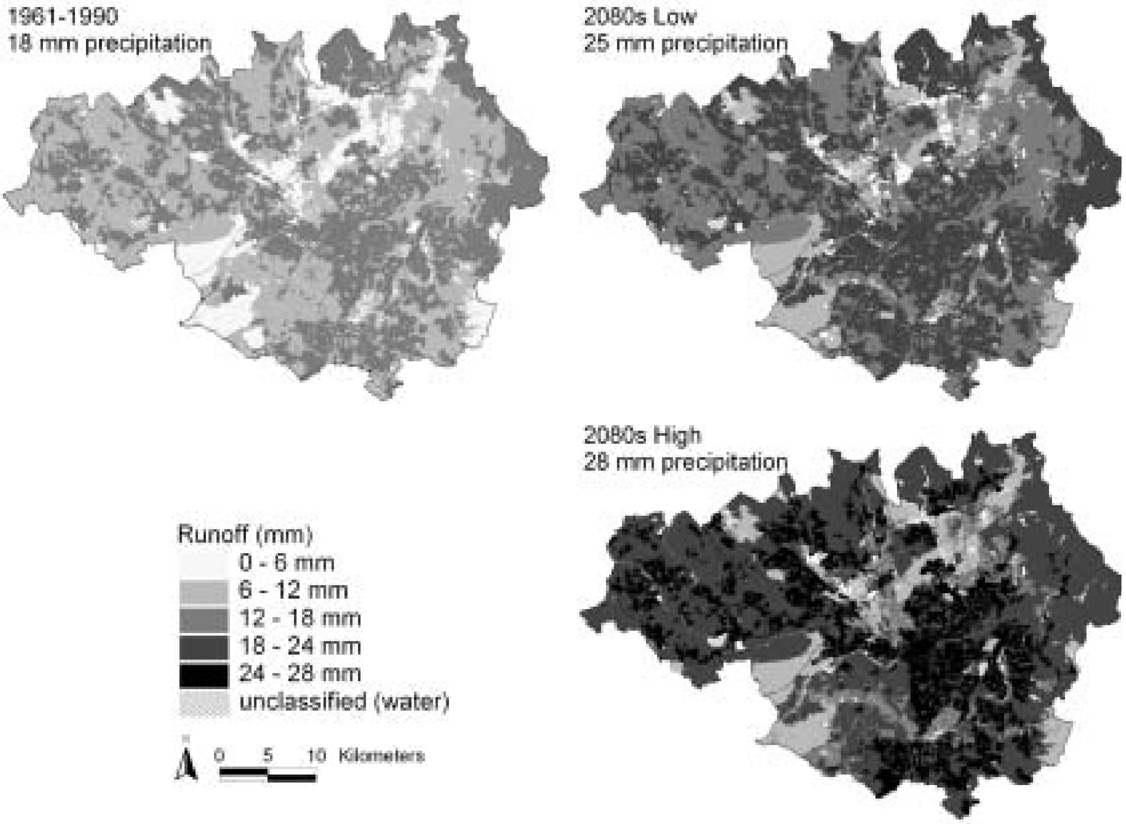

Figure 10. Surface runoff over Greater Manchester from 99th percentile daily winter precipitation with normal antecedent moisture conditions in 1961–1990 and the 2080s Low and High emissions scenarios.

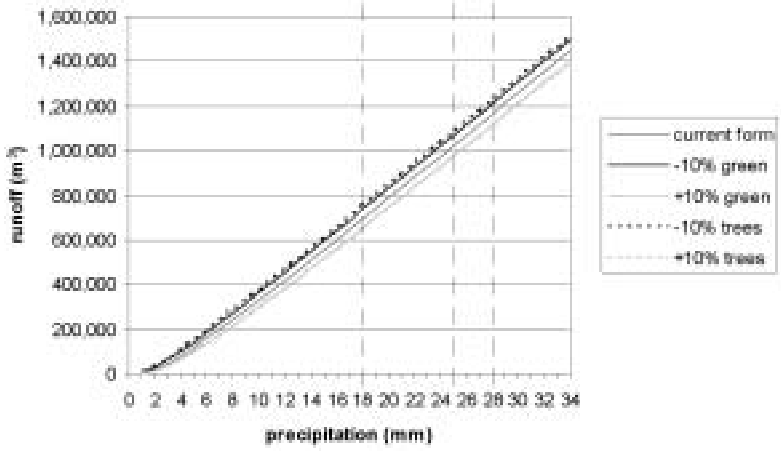

Figure 11. Runoff from high-density residential with current form and plus or minus 10 per cent green or trees, with normal antecedent moisture conditions. Vertical dashed lines show the 99th percentile daily winter precipitation for 1961–1990 (18 mm), the 2080s Low (25 mm), and the 2080s High (28 mm).

than the 18 mm event, the total Greater Manchester runoff increases by 82.2 per cent to 25.2 million m^3. The total runoff from ‘urbanized’ Greater Manchester is 8.9 million m^3 for an 18 mm rainfall event compared to 16.0 million m^3 for a 28 mm rainfall event.

Increasing green cover by 10 per cent in the residential UMTs reduces runoff from these areas from a 28 mm precipitation event, expected by the 2080s High, by 4.9 per cent; increasing tree cover by the same amount reduces the runoff by 5.7 per cent (figure 11). While increasing green or tree cover by 10 per cent helps to deal with the increased precipitation, it cannot keep the future runoff at or below the runoff levels for the baseline 1961–1990 current form case. In fact, runoff from high-density residential areas will still be approximately 65 per cent higher by the 2080s High even when green cover is added, when compared to the 1961–1990 current form case. This ‘development scenario’ does not have a very large impact on the total runoff over Greater Manchester; however, it must be remembered that residential areas cover 29 per cent of Greater Manchester. Thus, changing 10 per cent of the surface cover in residential areas in fact only alters 2.9 per cent of the surface of the conurbation. Adding 10 per cent tree cover to residential areas reduces total Greater Manchester runoff by only 1.9 per cent for a 28 mm event.

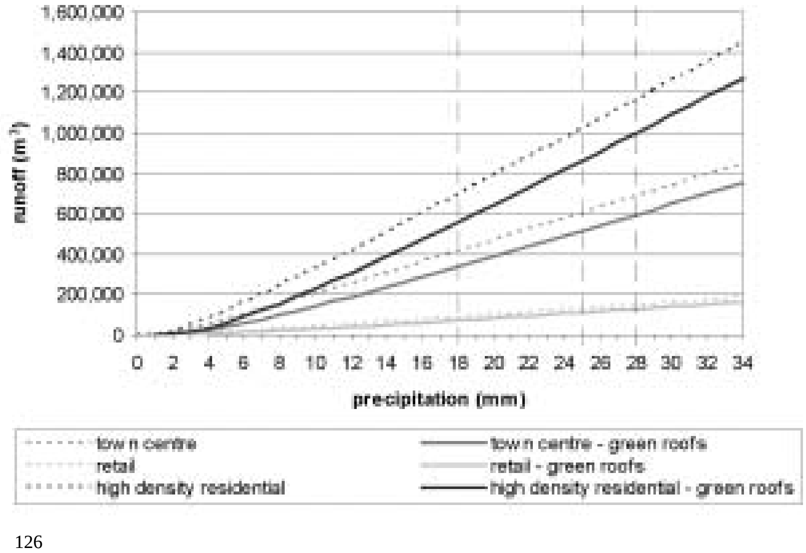

Figure 12. Runoff for selected UMTs with and without green roofs added, vertical dashed lines show the 99th percentile daily winter precipitation for 1961–1990 (18 mm), the 2080s Low (25 mm), and the 2080s High (28 mm).

Adding green roofs to all the buildings in town centres, retail, and high-density residential UMTs significantly reduces runoff from these areas (figure 12). The effect is greatest where there is a high building cover. When green roofs are added, the runoff from an 18 mm rainfall event for these UMTs is reduced by 17.0–19.9 per cent. Even for the 28 mm event runoff can be reduced by 11.8–14.1 per cent by adding green roofs. By the 2080s High, when compared to the 1961–1990 current form cases, adding green roofs to town centres, retail, and high-density residential UMTs limits the increase in runoff to 43.6 per cent, 47.2 per cent and 44 per cent, respectively. This is compared to 65.5 per cent, 67 per cent and 67.6 per cent for these areas if no green roofs were added.

Green roofs reduce the total Greater Manchester runoff for an 18 mm precipitation event by 0.6 per cent, 0.1 per cent, and 1.0 per cent when added to town centres, retail, and high-density residential, respectively; for a 28 mm event the reductions are 0.4 per cent, 0.1 per cent, and 0.7 per cent, respectively. Whilst these figures seem small, it must be remembered that town centres, retail, and high-density residential cover 2.1 per cent, 0.5 per cent and 3.7 per cent of Greater Manchester, respectively.

Climate Adaptation via the Green Infrastructure

The modelling work presented here suggests that the use of urban greenspace offers significant potential in moderating the increase in summer temperatures expected with climate change. Adding 10 per cent green in high-density residential areas and town centres kept maximum surface temperatures at or below 1961–1990 baseline levels up to, but not including, the 2080s High. Greening roofs in areas with a high proportion of buildings, for example in town centres, manufacturing, high-density residential, distribution and storage, and retail, also appeared to be an effective strategy to keep surface temperatures below the baseline level for all time periods and emissions scenarios. On the other hand, the modelling work highlights the dangers of removing green from the conurbation. For example, if green cover in high-density residential areas and town centres is reduced by 10 per cent, surface temperatures will be 7°C or 8.2°C warmer by the 2080s High in each, when compared to the 1961–1990 baseline case; or 3.3°C and 3.9°C when compared to the 2080s High case where green cover stays the same.

Thus, one possible adaptation strategy to increasing temperatures is to preserve existing areas of greenspace and to enhance it where possible, whether in private gardens, public spaces or streets. For example in Housing Market Renewal Areas or in the Growth Areas, significant new greenspaces should be created. These initiatives are part of the UK government's Sustainable Communities Programme. Nine Housing Market Renewal Areas have been identified by the government across the North of England and the Midlands, including Manchester / Salford and Oldham / Rochdale, with the objective of renewing failing housing markets through refurbishment, replacement and new build of houses. The Growth Areas are in South East England and will provide as many as 200,000 new homes to relieve housing pressures in the region (DCLG, no date). Given the long life time of buildings, from 20 to over 100 years (Graves and Phillipson, 2000), it is crucial to take opportunities for creating greenspaces as they arise.

However, in many existing urban areas where the built form is already established, it is not feasible to create large new greenspaces. Thus, greenspace will have to be added creatively by making the most of all opportunities, for example through the greening of roofs, building façades, and railway lines, street tree planting, and converting selected streets into greenways. Priority should be given to areas where the vulnerability of the population is highest. A study in Merseyside found that vegetation, and in particular tree cover, is lower in residential areas with higher levels of socio-economic deprivation (Pauleit *et al.*, 2005). The socio-economic deprivation index used included variables relating to health deprivation. Such populations will therefore be more vulnerable to the impacts of climate change.

One caveat to the potential of green cover in moderating surface temperatures is the case of a drought, when grass dries out and loses its evaporative cooling function. Output from the daily weather generator used suggests that with climate change there will be more consecutive dry days and heat waves of longer duration in summer (BETWIXT, 2005; Watts *et al.*, 2004*a*, 2004*b*). Similarly, research undertaken as part of the ASCCUE project to map drought risk through the combination of available water in the soils, precipitation and evapotranspiration, suggests a significant increase in the duration of droughts with climate change. Thus, it is likely that there will be more cases when the grass loses its evaporative cooling function unless counter measures are taken. In such situations the role of water surfaces in providing cooling and trees in providing shade become increasingly important. The modelling work presented here does not include the effect of shading on surface temperatures. A pilot study undertaken by the ASCCUE project suggests that the shade provided by mature trees can keep surfaces cooler by as much as 15.6°C.

One possible adaptation strategy would be drought-resistant plantings. In Greater Manchester this would involve planting vegetation, such as trees, that is less sensitive than grasslands to drought. Trees are common in open spaces in the Mediterranean. Tree species which are less sensitive to drought can be chosen from temperate zones, such that they will still evapotranspire and provide shade. Site conditions for trees in streets may need improving so that there is sufficient rooting space. In addition, irrigation measures must be considered to ensure that they have an adequate water supply. This could be through rainwater harvesting, the re-use of greywater, making use of water in rising aquifers under cities where present, and floodwater storage. Unless adequate provision is made there will be conflict as greenspace will require irrigating at the same time as water supplies are low and restrictions may be placed on its use. Ironically, measures which are currently in hand to reduce leakage in the water supply system may reduce available water for street trees which are critically important for human comfort in the public realm.

There may be other potential conflicts arising from planting trees in proximity to buildings. On clay soils in particular, changes in soil moisture content, as may occur with climate change, result in dimensional changes in the soil (Percival, 2004). If changes occur below the foundation level of the buildings, this can result in damage. However, the persistence of a moisture deficit beyond seasonal fluctuations only occurs in extreme cases. Tree roots are involved in at least 80 per cent of subsidence claims on shrinkable clay soils, yet even on clay soils the risk of a tree causing damage is less than 1 per cent (Biddle, 1998). Biddle (1998) argues that, due to the importance of trees in urban environments, a proper understanding is required of the mechanism of damage, how this can be prevented, and of appropriate remedies if damage occurs. An approach which accepts that minor damage may sometimes occur, and then remedies the situation if it does, is the most appropriate. In addition, new buildings should include precautions in the design and construction of foundations to allow for tree growth near buildings (Biddle, 1998).

The modelling work suggests that greenspace on its own is less effective at moderating the volume of surface runoff under climate change. While greenspace helps to reduce surface runoff, especially at a local level, the increase in winter precipitation brought by climate change is such that runoff increases regardless of changes to surface cover. Thus, in order to adapt to the increased winter precipitation expected with climate change, greenspace provision will need to be considered alongside increased storage. There is significant potential to utilize sustainable urban drainage (SUDS) techniques, such as creating swales, infiltration, detention and retention ponds in parks (Mansell, 2003; CIRIA, 2000). There is also an opportunity to store this excess water and make use of it for irrigating greenspaces in times of drought.

Another way of exploring possible climatic adaptations is to consider the green infrastructure of the conurbation from the perspective of landscape ecology. The modelling work has concentrated on the environmental performance of the UMTs regardless of their spatial context. However, the functionality of the green infrastructure will be dependent on its location. Thus, the green infrastructure can be viewed as consisting of corridors, patches, and the overall matrix (figure 13) (Forman and Godron, 1986).

These components of the green infrastructure play different roles in terms of climatic adaptation (table 2). For example, flood storage is especially important in corridors, but also has some importance as SUDS in the patches. In Greater Manchester, for example, green spaces such as golf courses and nature reserves alongside the River Mersey are used as flood storage basins at times of high river flow (Sale Community Web, no date). On the other hand, the matrix is especially important when it comes to rainwater infiltration, as are patches. Greenspace is most effective at reducing surface runoff on sandy, faster infiltrating soils. There may be a case for adapting to climate change through preserving and enhancing vegetated surfaces on such soils, for example, through the creation of Conservation Areas. Infill development could be restricted in lower density residential areas where soils have a high infiltration capacity. Evaporative cooling is very important in the patches which provide green oases with cooler microclimates and also in the matrix where people live. Greenspaces develop a distinctive microclimate when they are greater than 1 hectare (von Stülpnagel *et al.*, 1990). Similarly shading is required in the matrix and patches, especially within residential areas.

In addition to providing climate adaptation, the green infrastructure offers a range of other benefits in urban areas (e.g. URBED, 2004; Givoni, 1991). The combination of these functions makes the use of green infrastructure an attractive climate adaptation strategy. Moreover, the use of green infrastructure may help in reducing greenhouse gas emissions, or in mitigating climate

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Figure 13. Elements of the green infrastructure from a landscape ecological perspective.

Table 2. Climate adaptation via the green infrastructure – an indicative typology.

	Corridor	*Patch*	*Matrix*
Flood storage	• • •	• •	•
Infiltration capacity	•	• •	• • •
Evaporative cooling	•	• • •	• •
Shading	•	• •	• • •

change. For example, vegetation can reduce solar heat gain in buildings and can thus reduce the demand for mechanical cooling through air conditioning, which contributes both the greenhouse gas emissions as well as the intensification of the urban heat island through waste heat (e.g. Niachou *et al.*, 2001; Onmura *et al.*, 2001; Papadakis *et al.*, 2001).

Conclusion

The research findings presented here are significant because they begin to quantify the potential of the green infrastructure to moderate climate change impacts in towns and cities. Such claims are often made for urban greenspace (e.g. Hough, 2004) but the introduction of a modelling approach clarifies the magnitude of the effect and allows adaptation strategies to be tested. We do not suggest that the model outputs can be directly translated in practice, for example it would be quite unrealistic to green all roofs in city centres and high-density residential areas. However, the model runs indicate which type of actions are likely to be most beneficial and in which locations. Urban greenspace from street trees, to private gardens, to city parks provide vital ecosystem services which will become even more critical under climate change.

Within urban centres green spaces therefore constitute critical environmental capital that, once developed, is difficult to replace. This green-space needs to be strategically planned. The priorities for planners and greenspace managers is to ensure that the functionality of greenspace is properly understood and that what exists is conserved. Then it should be possible to enrich the green cover in critical locations, for example the planting of shade trees in city centres, schools and hospitals. Opportunities to enhance the green cover should also be taken where structural change is taking place, for example, in urban regeneration projects and new development. The combination of the UMT-based modelling approach with the patch-corridor-matrix model may help in the development of spatial strategies for the green infrastructure to preserve existing greenspace and create new greenspace such that a functional network is formed. This approach, however, requires further exploration.

Mature trees will be very important for the roles they play in providing shade and intercepting rainfall. Also, in times of drought they may provide a cooling function for longer than grass, which will dry out faster. At present, those areas experiencing highest surface temperatures and socio-economic disadvantage also have the lowest tree population and here urban forestry initiatives, such as the Green Streets project of the Red Rose Forest of Greater Manchester (Red Rose Forest, no date), are beginning to redress the balance. During periods of water shortages, as for example in South East England at the time of writing, urban vegetation is often the first target of a ‘drought order’. The research suggests that the benefits of greenspace go well beyond consideration of amenity and that opportunities will have to be taken to ensure an adequate water supply to vegetation in times of drought.

Climate change is already with us and there is an urgent need to develop adaptive strategies. The creative use of the green infrastructure is one of the most promising opportunities for adaptation and this needs to be recognized in the planning process at all scales from the Regional Spatial Strategies, through Local Development Frameworks to development control within urban neighbourhoods. Within the government's Sustainable Communities Programme there is real scope to 'climate proof' new developments in the Growth Areas and to reintroduce functional green infrastructure during the redevelopment process in areas subject to Housing Market Renewal.

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