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Green infrastructure as an adaptation approach to tackling urbanoverheating in the Glasgow Clyde Valley Region, UK

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Highlights:

- Classification of urban areas into local climate zones (LCZ)
- CFD simulation of green cover in mitigating climate change and heat island effects
- 20% increase in green cover could reduce surface temperatures by 2^{o}C in 2050
- Green infrastructure option to achieve 20% increase in greenery are presented

Abstract

Although urban growth in the city of Glasgow, UK, has subsided, urban morphology continues to generate local heat islands. We present a relatively less data-intense method to classify local climate zones (LCZ) and evaluate the effectiveness of green infrastructure options in tackling the likely overheating problem in cold climate urban agglomerations such as the Glasgow Clyde Valley (GCV) region. LCZ classification uses LIDAR data available with local authorities, based on the typology developed by Stewart and Oke (2012). LCZ classes were then used cluster areas likely to exhibit similar warming trends locally. This helped to identify likely problem areas, a sub-set of which were then modelled for the effect of green cover options (both increase and reduction in green cover) as well as building density options.

Results indicate green infrastructure could play a significant role in mitigating the urban overheating expected under a warming climate in the GCV Region. A green cover increase of approximately 20% over the present level could eliminate a third to a half of the expected extra urban heat island effect in 2050. This level of increase in green cover could also lead to local reductions in surface temperature by up to 2oC. Over half of the street users would consider a 20% increase in green cover in the city centre to be thermally acceptable, even under a warm 2050 scenario. The process adopted here could be used to estimate the overheating problem as well as the effectiveness green infrastructure strategies to overcome them.

1. Introduction

In the face of growing consensus on the anthropogenic causes for global climate change (see IPCC, 2013) and the lag-times involved in the mitigation of such changes, there is considerable focus on the enhancement of adaptive capacity of human systems to cope with climate change. Given the rapid rise in global urbanisation much of the adaptive action needs to occur in cities. However, research on the augmentation of climate change effects by local urban warming (characterised by urban heat islands) remains weak. A key difficulty in untangling the urban warming from global climate change is the computational and parametric difficulties associated with representing urban areas in climate models (Jin et al., 2005; Grawe et al., 2013). Additionally, translating future climate change projections at finer spatial scales relevant to cities typically use statistical downscaling techniques to global climate models without modelling the urban areas themselves (Lemonsu et al., 2013) a technique not without problems. Although the situation is continuing to improve (cf. Hebbert and Jankovic, 2013) much more still need to be done to (a) ameliorate the urban heat island (UHI) effect and (b) use UHI mitigation as part of climate change adaptation.

World's shrinking cities face additional problems in managing climate change. Previous work in Glasgow (Emmanuel and Kruger, 2012; Kruger et al., 2013) – one such 'shrinking city' – indicates that even when urban growth has subsided, the local warming that result from urban morphology (increased built cover, lack of vegetation, pollution, anthropogenic heat generation) continue to generate local heat islands. Such heat islands are of the same order of magnitude as the predicted warming due to climate change by 2050. And the micro-scale variations are strongly related to local land cover/land use patterns. However, current climate change adaptation strategies are more focussed on reducing carbon emission than managing the change via land use / land cover manipulations, even though the latter is relatively easier to manage in shrinking cities.

Given these realities, it is necessary to explore the role of land cover changes especially green infrastructure changes, as potential climate change adaptation options. Specifically, it is necessary to quantify the scale of green infrastructure changes needed in specific cities and explore ways to accomplish them. It in this light the present paper explores the role of green cover in areas of different urban density within the Glasgow Clyde Valley (GCV) Region in the central belt of Scotland. It characterises the urban pattern within the GCV in terms of their local warming attributes, using a classification system known as the Local Climate Zones (LCZ) (Stewart and Oke, 2012). Such classification could help identify areas most likely to experience significant overheating problem in the future (cf. Lelovics et al., 2014). Computational fluid dynamics (CFD) simulations are then carried out to test the applicability of green infrastructure approaches. Alternative strategies to enhance the green cover in a Glasgow city centre neighbourhood are presented.

The rest of the paper is structured in five sections: Section 2 presents background evidence to the presence of the heat island phenomenon in Glasgow and the two techniques commonly used to study it (local climate zones to classify urban areas and ENVI-met, a CFD model commonly used to study the effectiveness of mitigation strategies). Sections 3 and 4 detail the land cover/land use classification employed in the present study. Section 5 presents the results of the simulation exercise and Section 6 explores the implications of the results. It is hoped that the method of classifying LCZ using relatively easily available data as well as the exploration of green infrastructure in ameliorating the likely overheating problem could be applicable to other cold climate cities.

2. Background

2.1 Glasgow's heat island phenomenon

Based on a four-pronged approach to map the local climate variations in and around the city of Glasgow in 2011 (historic climate trends in the city; fixed weather station data in and around the city; microclimate variations at the street canyon level within the city core, and thermal perception of street users in the heart of the city centre) Emmanuel and Kruger (2012) and Kruger et al., (2013) found the following:

1. Even when urban growth has subsided, the local warming that result from urban morphology (increased built cover, lack of vegetation, pollution, anthropogenic heat generation) continue to generate local heat islands;
2. Such heat islands are of the same order of magnitude as the predicted warming due to climate change to 2050;
3. Substantial variations within city neighbourhoods exist and these relate to land use/land cover attributes, pointing to planning possibilities to locally mitigate the negative consequences of overheating;
4. Strategies to tackle local overheating can lead to less carbon intensive enhancement of comfort, health and quality of life both within and outside buildings.

Given the geographic and urban growth similarities of the GCV region to that of the city of Glasgow, the overheating problem in the GCV area is likely to be similar. Carefully planned development of urban morphological variables such as the green infrastructure offers possibilities to enhance outdoor livability and reduced building energy use in the immediate future when the regional climate remains relatively similar to current conditions, but also provides an adaptive mechanism when the background climate continues to warm (Kleerekoper et al., 2012), thus lending itself to be a useful strategy to adapt to climate change in the GCV region, both in the immediate- and long-term.

2.2 Local Climate Zone classification

In order to characterise the land use / land cover patterns in areas of interest, we used the 'Local Climate Zone' (LCZ) system developed by Stewart and Oke (2012). LCZs are defined as 'regions of uniform surface-air temperature distribution at horizontal scales of 10^2 to 10^4 metres' (Stewart and Oke, 2012). Their definition is based on characteristic geometry and land cover that is expected to generate a unique near-surface climate under calm, clear skies. These include vegetative fraction, building/tree height and spacing, soil moisture, and anthropogenic heat flux. LCZ has 16 climate zones and the classification system has been validated in Sweden, Japan and Canada (Stewart and

Oke, 2009) and widely used in other contexts (for example, Lelovics et al., 2014; Middel, et al., 2014; Villadiego and Velay-Dabat, 2014).

Although the LCZ classification system was not developed for mapping the UHI effect but to assist in the selection of locations for local weather stations and to report heat island effect in a standardised manner, it is a useful system to identify micro-climatically distinguishable areas within an urban agglomeration, and this aspect of the LCZ is useful in identifying the likely local warming effects of urban development. This was indeed shown to be true in Glasgow (see Figure 12 in Emmanuel and Kruger, 2012).

2.3 CFD simulations in UHI studies

The non-linearity of the UHI problem lends itself to numerical simulations and is therefore increasingly popular in urban climatology (Saneinejad et al, 2014). Urban microclimate models vary widely with regard to their physical basis and spatial/temporal resolution. Ali-Toudert & Mayer (2006) provide a detailed critique of contemporary models at the micro-scale with fine temporal resolutions. They inferred that ENVI-met (Bruse 1999, 2004) is perhaps the only micro-scale computational fluid dynamic model that is capable of analyzing the thermal comfort regime within the street canyon at fine resolutions (down to 0.5×0.5 m). ENVI-met is increasingly being used to assess the effectiveness of urban planning measures to tackle the UHI problem in a variety of climate contexts (for example, Ketterer and Matzarakis, 2014 – Stuttgart, Germany; Chen and Ng, 2013 – Hongkong SAR; Emmanuel et al., 2010 – Colombo, Sri Lanka; Middell et al., 2014 – Phoenix, USA; Skelhorn et al., 2014, Manchester, UK).

ENVI-met is a three-dimensional non-hydrostatic model for the simulation of surface–plant–air interactions, especially within the urban canopy layer. It is designed for the micro-scale with a typical horizontal resolution from 0.5 to 10 m and a typical time frame of 24 to 48 h with a time step of 10 s. This resolution allows the investigation of small-scale interactions between individual buildings, surfaces and plants (Bruse 2004).

Input meteorological data required to initiate ENVI-met simulations are: wind speed and direction at 10 m above ground, roughness length (Z_o), initial temperature of the atmosphere, specific humidity at 2500 m and relative humidity at 2 m. The model calculation includes surface and wall temperatures for each grid point and wall and the calculation of bio-meteorological parameters such as the Mean Radiant Temperature (MRT) or Predicted Mean Vote (PMV) (Fanger 1970).

A shortcoming of ENVI-met is that buildings, which are modelled as blocks where width and length are multiples of grid cells, have no thermal mass and have constant indoor temperature. Moreover, albedo and thermal transmission (U-value) for walls and roofs are the same for all buildings. However, it is an effective tool for the analysis of urban temperature at the micro-scale with fine temporal resolutions (Ali-Toudert & Mayer, 2006).

3. Method

The pursuit of green infrastructure strategies to tackle the overheating problem due to climate change enhanced by local warming in the GCV required the following steps:

1. Identification of localities where local warming is likely to be the most intense (the 'hot spots');
2. Estimation of the likely future climate (in 2050);
3. Evaluation of the sensitivity of green infrastructure-based adaptation options to reduce the 'hot spots' under future climate.

We classified the GCV region into LCZ classes using Ordnance Survey (OS) and LiDAR data to estimate surface characteristics such as building cover, building height, land cover and/or land use. Ordnance Survey is the UK's national mapping authority providing detailed land cover information and its data are available free of charge at: https://www.ordnancesurvey.co.uk. Vector files containing the following layers were downloaded for the National Grid No. NS26, which covers all of the GCV Region. More details on the National Grid are available at: http://www.ordnancesurvey.co.uk/docs/support/national-grid-map-references.pdf. Each square contains land cover data for a 100 x 100 km area. Light Detection And Ranging (LiDAR) data is an accurate, high resolution three-dimensional data used to create highly detailed digital surface models that could eventually be turned into three dimensional city models. LiDAR technology allows large area models to be created in a very short space of time. LiDAR data for the present study area was provided by the Glasgow Clyde Valley Green Network Partnership (http://www.gcvgreennetwork.gov.uk/) which itself obtained the data from the local authorities in the GCV region. Additional ground truth verification of selected representative areas using 'Google Earth' and site visits helped verify building height and other physical parameters. Future climate data were obtained from the UK Climate Projections 2009 – UKCIP'09 (http://www.ukcip.org.uk/). UKCIP'09 is the fifth generation of climate change information for the UK and is based on inductive probability (i.e. estimations are based on the available information and strength of evidence instead of taking into account all the possible outcomes)

The evaluation of the effect of green infrastructure was carried out using ENVI-met simulations. Six scenarios were run as detailed below. :

1. 2012 climate with current development pattern = 'Current Case;'
2. 2050 climate (using UKCIP'09 projections) with current level of development – 'Base Case';
3. 2050 climate with 'loss' of green infrastructure ('m10 case')
4-6. 2050 climate with three levels of increased green cover (+10%, +20% and +100% relative to the existing case – p10, p20 and p100 cases, respectively)

Based on the simulation results we estimated the minimum green cover needed to make a significant difference to the likely local warming in 2050. We then used the Green Area Ratio method (Keeley, 2011) to normalise the climatic effects of different types of green cover (urban parks, street trees, green roofs, green walls, etc).

3.1 Green Area Ratio (GAR) method

Not all green areas contribute equally to local cooling nor are they equal in their other environmental and sustainability benefits. Recognising this, planning authorities have developed weighting systems that captures the relative environmental performance of different types of green cover. The most widely used among these is the Green Area Ratio (GAR) method (Keeley, 2011). GAR assigns weighting factors for different types of urban green infrastructure, based on their relative environmental performance in terms of climate change mitigation. It is currently implemented in Berlin and has been adapted in Malmo (Sweden), several cities in South Korea and Seattle (USA) (Keeley, 2011). Table 1 shows the relative weighting of different types of green cover.

(Table 1 here)

4. Effect of land use / land cover and local climate

The key to understanding the local climatic effect of land cover/land use characteristics is to classify the settlement area according to their key climate-influencing features.

4.1 Site selection using the LCZ approach

The following steps were performed to determine the dominant LCZ classes in the GCV region and thus select 'representative' sample locations where local warming is likely to be problematic.

1. Determine the 'developed' areas of the GCV
2. Calculate built fraction / natural cover within 1km dia circles placed in an array covering the entire 'developed' area in the GCV identified in step 1
3. Classify each circle into relevant LCZ class, depending on built/green fraction and building height closely matching the urban morphological parameters shown in Table 2
4. Select sample locations representing the different LCZ classes available within the GCZ

(Table 2 here)

The aim of the first step was to reduce the area of enquiry to 'developed' areas within the urban agglomeration to limit the computational time needed. We first downloaded the data for the area of interest from the ordnance survey open database. The GCV Region covers only a small part of the 100x100km NS square (NS26, see Section 3), and the 'developed' area within the relevant NS square was clipped and a 1km x 1km grid was placed over it. This resulted in 1519 grid points on the 1km x

1km grid and a circle of 500m in radius was added to each point to carry out Step 2. Step 2 then calculated the built cover (building footprints and roads) as well as the 'natural' cover. The building cover were divided into categories (depending on their three dimensional properties.

Step 3 (determination of the LCZ class of each 1km dia. Circle) was carried out as follows: Four small circles (500m dia.) were created within each large circle (See Figure 1). The percentages of buildings, roads, inland water and natural cover were calculated for each of the 500m dia. circles using ArcGIS (v.10.1) and averaged to derive at the land cover types for each of the 1km radius circle. Figure 2 shows the results of Step 3.

(Figure 1 here)

(Figure 2 here)

It could be seen from Figure 2 that the GCV region largely composes of two classes of 'semi-dense' urban morphology (LCZ 2 and 3 – Compact midrise, mainly Glasgow City centre) and three classes of 'sparse' settlement morphology (LCZ 5 – Open midrise; LCZ 6 – Open lowrise; LCZ 9 – Sparsely built).

Based on these results Step 4 selected six sites. In addition to representing the variations in LCZ classes this step also considered the location of local weather stations, the data from which could be useful in initiating the ENVI-met model runs for each of the selected sites. The selected sites are listed below (See Figure 3 for locations and Figure 4 for three-dimensional details):

1-2. LCZ 2 – Compact midrise two locations characterising this class: Glasgow City Centre West (Gla CCW) centred on the intersection of W Campbell Street & Bath Street (Coordinates – British National Grid; map projection: transverse Mercator; datum: OSGB: 36258595.665 – 665800.603 Meters) and Glasgow City Centre East (Gla CCE) comprising an area surrounding the George Square area, centred on the intersection of John Street & Ingram Street (259339.524 – 665260.852 Meters);

3. LCZ 6 – Open lowrise: Clyde Gateway area (London Road & Springfield Road) (260683.157 – 663742.061 Meters);

4. LCZ 5 – Open midrise: Paisley area (High Street & New Street) (248146.997 – 663988.741 Meters)

5-6. LCZ 9 – Sparsely built (or extensive lowrise): two locations characterising this class Wishaw (Caledonia Rd. and Main St.) (279691.562 – 655018.654 Meters), and Hamilton (Brandon St. and Quarry St.) (272438.576 – 655517.511 Meters)

(Figure 3 here)

(Figure 4 here)

Land cover characteristics of the individual sites are shown in Figures 5-9 (Note Sites 1 and 2 are covered by Figure 5). Each figure shows the land cover as given in the Ordnance Survey maps (see 'Legend' at bottom left). These were amalgamated into categories relevant to LCZ (bottom right) as follows:

Built cover = Building, Structure, Structure on path, Glasshouse;
Natural = Natural Environment, Natural Environment along road or track;
Transportation = Road or Track, Roadside, Rail, Path
Water = Tidal Water, Inland Water
Open Surface = General Surface
Unclassified = Landform, Unclassified, Landform along road/track

(Figure 5 here)

(Figure 6 here)

(Figure 7 here)

(Figure 8 here)

(Figure 9 here)

5. Simulation of the effects of green infrastructure in the GCV

The performance of ENVI-met was validated for Glasgow, using a process described by Loconsole (2013). We used data from a weather station set up on the city campus of Glasgow Caledonian University (55.86611^{o}N, 4.25^{o}W) for this purpose. For the turbulence closure of the atmospheric boundary layer we used the prognostic κ-ε model while the turbulence closure of the 3D model and the upper boundary employed the prognostic 1.5 order κ-ε closure model and κ-ε closed model (fixed value) respectively. The lateral boundary conditions for both temperature and humidity as well as Total Kinetic Energy are set as open so the values of the next grid point close to the border are copied to the border at each time step.

(Table 3 here)

We performed several ENVI-met model runs to derive appropriate input parameters. Table 3 shows the changes made to input parameters, domain size, grid size etc. With regard to the computational domain and the grid size, two settings were tested during the setup process: 80x80x30 grids (grid size = 5m x 5m x 3m) resulting in a 400m x 400m domain and 80x80x30 grids (grid size = 20m x 20m x 3m) resulting in a 1600m x 1600m domain. The first domain size was chosen taking into account the minimum LCZ spatial definition while the second accounted for the maximum LCZ spatial definition. However, given the extremely time consuming nature of the simulation of the larger domain (over 100 hrs per simulation) it was decided to use the 400m x 400m domain throughout the present work.

Figure 10a shows the results of simulated and measured temperatures in the city of Glasgow on 30 April 2011. Figure 10b shows the comparison for the daytime (06:00 -18:00 hrs) (Root Mean Square Error [RMSE] = 0.83 and R^2 = 0.9461). This compares well with the results of Skelhorn et al., (2014) for Manchester where the correlation between the measured and modelled temperatures during 09:00-midnight were R^2 = 0.9393. Figure 10b also indicates that the model over-predicts during the nighttime and under-predicts during the day. Given the use of the model in the present paper (comparison of cooling effects of green infrastructure during the day) this limitation is therefore likely to err on the conservative side.

(Figure 10a here)

(Figure 10b here)

5.1 Air temperature effects

During the daytime the different green cover scenarios result in little variation in air temperature while the suburban/rural sites show marked decrease in air temperature at increased levels of green cover (Figure 11). The situation at nighttime (Figure 12) is different, in that there is a consistent pattern of cooling at all sites.

(Figure 11 here)

(Figure 12 here)

Figure 13 shows the average cooling expected over the course of summer in 2050. The overall effect of green cover on air temperature under future climate scenario is encouraging.

(Figure 13 here)

Figure 14 shows the level at which green cover makes the most impact is approx. 20% above the current level, with diminishing returns thereafter. At this level of green cover a net cooling of 0.3^{o}C can be expected in 2050. This would be about a third of the extra heat island effect predicted for the Glasgow conurbation (Kershaw et al., 2010).

(Figure 14 here)

The range in temperature change due to green cover change across the entire simulated domain (400m x 400m area) is tabulated Table 4. A vast majority of pixels – i.e. to 91.2% (Glasgow City Centre) – 99.8% (Wishaw) of the simulated area – showed up to 0.5^{o}C reduction in air temperature. Based on the expected heat island effect for the Glasgow area this local cooling effect would be more than half of the total urban warming expected in 2050. The case of Gla CC-E (around George Square) is interesting, in that the lack of green cover increase could lead to 19% of the area showing a slight increase (up to 0.25^{o}C) in temperature under the 2050 base case scenario.

(Table 4 here)

5.2 Surface temperature effects

In addition to calculating air temperatures, ENVI-met also produces surface temperatures within the model domain area (Figure 15 [daytime] and Figure 16 [nighttime]). There is a marked decrease especially during the day and in conjunction with increased shading/green cover (city centre sites) or increased green cover (suburban sites).

(Figure 15 here)

(Figure 16 here)

While surface temperatures are particularly susceptible to the vagaries of local shading (or lack thereof) the purpose here was to compare results with that of other UK cities, most notably Manchester (Gill et al., 2007) where a 10-20% increase in green cover led to up to 4^{o}C decrease in surface temperature while green roofs in city centre led to a lowering of surface temperature by up to 6^{o}C. Given the influence of surface temperature on the Mean Radiant Temperature (T_{MRT}) it is also noteworthy that Klemm et al (2015) found a 1 K drop in T_{MRT} for a 10% increase in street tree cover in Utrecht, Netherlands – whose climate is similar to that of Glasgow (Köppen classification = Cfb).

5.3 Thermal comfort implications of green cover

A commonly used measure of human thermal perception is the Predicted Mean Vote (PMV), based on BS EN ISO 7730 (2005). PMV is a 'comfort vote' on a 7-point scale that takes into account environmental factors such as air temperature, relative humidity, air velocity and MRT as well as personal attributes such as clothing and level of activity. Although PMV was originally developed for the estimation of indoor comfort previous work (Kruger et al., 2012) found it had good agreement with street users' subjective thermal sensation in Glasgow's outdoors (R^2 = 0.987).

ISO 7730 specifies a range of -1.0 to +1.0 within which approximately 75% of the subjects would be 'satisfied' with their thermal environment.

(Table 5 here)

Based on ISO 7730 (i.e. a 'comfort vote' between -1.0 to +1.0 is acceptable to a majority of street users) 52.5-54.6% of the users in city centre would consider 2050 climate acceptable if a 20% increase in green cover could be provided (Table 5). However 36.6-40% of the users in the city centre will still feel 'hot' under such a scenario. A combination of 20% greenery with tall buildings in the city centre (not shown in the present paper) would lead to 72.8-86% of the users feeling comfortable (Table 6). In suburban and less built up areas however, Tables 3 and 4 indicate the thermal comfort effect of green cover will be more muted. A 100% increase in green cover will be required to make significant improvement in perceived thermal comfort in three of the four less built up sites (Paisley, Clyde Gateway and Hamilton).

(Table 6 here)

6. Implications and Conclusions

The simulation work carried out by the present study indicates that green infrastructure could play a significant role in mitigating the urban overheating expected under a warming climate in the GCV Region. Our work also indicates that a green cover increase of approximately 20% over the present level could eliminate a third to a half of the expected extra urban heat island effect in 2050. This level of increase in green cover could also lead to local reductions in surface temperature by up to 2^{o}C. Furthermore, over half of the street users would consider a 20% increase in green cover in the city centre to be thermally acceptable, even under a warm 2050 scenario. Additional strategies such as increased building cover could further improve the thermal comfort and air temperature patterns in the city centre.

6.1 Achieving green cover increase – an example

In practical terms a 20% increase in green cover could be achieved in a number of different ways: mini-parks, street trees, grass areas, roof gardens, green walls or even urban forests. We used the GAR method (See section 3.1) to develop alternate arrangements that could achieve a 20% increase in green cover.

Table 7 here

Table 7 shows the assumptions made and the method used in attempting to deliver a 20% increase in green cover in Glasgow city centre, using green parks, street trees, green roofs, green façade or a combination of these. Based on these the following fractions of green cover are possible in the Gla CC-W domain area (all fractions expressed as percentage of the total simulated domain area):

Current green cover = 3.3%
Possible street tree cover = 3.72%
Possible roof area available for roof garden = 21%
Possible façade cover available = 6.34%

(Table 8 here)

Table 8 shows some options to achieve 20% green cover increase at the Glasgow city centre west (Gla. CC-W) site using the weightings shown in Table 1. These range from introducing a 1,056m^2 (32.5m x 32.5m) park to planting up to 528 new street trees to extensive roof gardens up to 1,056m^2 or introducing 1,268m^2 of green façade at this site.

The amelioration of urban heat island has a long pedigree and cities have adapted to local warming for a very long time (cf. Hebbert and Jankovic, 2013). Green infrastructure is long known to have a positive impact on the minimisation of the UHI effect (Gill et al., 2007). The present work shows an easy-to-use method to classify the urban landscape into Local Climate Zones and then to use this to select 'representative' locations to test the efficacy of green infrastructure in ameliorating the expected overheating problem under a changing climate in the GCV. The extent of green cover necessary to make a cooling impact is modest, and there are several options to achieve this. More work will be needed to evaluate the relative merits of specific green infrastructure interventions at specific urban sites. Furthermore, urban governance mechanisms (Foo et al., 2015) and institutional barriers to green infrastructure planning (Mathews, 2015) need additional research. However, the present work indicates green cover could be a future adaptation strategy to at least partially overcome the urban overheating problem expected under a warming climate.

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Table 1: Relative environmental performance weightings for different green infrastructure

Source: Based on Keeley 2011

Technique / cover type	Rating	Description
Impermeable surfaces	0.0	Surfaces that do not allow the infiltration of water. Includes: roof surfaces, concrete, asphalt and pavers set upon impermeable surfaces or with sealed joints
Impermeable surfaces, from which all stormwater is infiltrated on property	0.2	Includes surfaces that are disconnected from the sewer system. Collected water is instead allowed to infiltrate on site in a swale or rain garden. Guidelines for preventing groundwater and soil contamination must be followed
Non-vegetated, semi-permeable surfaces	0.3	Cover types that allow water infiltration, but do not support plant growth. Example include: brick, pavers and crushed stone
Vegetated, semi-permeable surfaces	0.5	Cover types that allow water infiltration and integrate vegetation such as grass. Examples include: wide-set pavers with grass joints, grass pavers and gravel-reinforced grassy areas
Green façades	0.5	Vines or climbing plants growing (often from ground) on training structures such as trellises which are attached to a building. The façade's area is measured as the vertical area the selected species could cover after 10 years of growth up to a height of 10m; window areas are subtracted from the calculation
Extensive green roofs	0.5	Green roofs with substrate/soil depths of less than 80 cm. However, Berlin excludes green roofs constructed on high-rise buildings
Intensive green roofs and areas underlain by shallow subterranean structures	0.7	Green roofs with substrate/soil depths of greater than 80 cm. This category includes subterranean garages
Vegetated areas	1.0	Areas which allow unobstructed infiltration of water without evaluation of the quality or type of vegetation present. Examples range from lawn to gardens and naturalistic wooded areas

Table 2: Properties of Local Climate Zone (LCZ)

Local Climate Zone (LZC)	Zone Properties							
	Ψ_{sky}	H:W	SF	Z_H	RC	α	μ ($J\ m^{-2} s^{½} K^{-1}$)	Q_F (Wm^{-2})
Compact Highrise	0.25-0.45	>2	>90%	>35m	8	0.12-0.18	1,200-1,700	100-150
Open-set Highrise	0.40-0.70	0.75-1.25	50-75%	>30m	7-8	0.12-0.20	1,200-1,700	20-35
Compact Midrise	0.30-0.60	0.75-1.25	>90%	15-25m	6-7	0.15-0.20	1,200-2,000	30-40
Open-set Midrise	0.80-0.90	0.20-0.30	30-50%	10-25m	5-6	0.15-0.20	800-1,500	<10
Compact Lowrise	0.30-0.50	1.00-1.50	>80%	3-10m	6	0.12-0.20	1,200-1,500	25-35
Open-set Lowrise	0.55-0.75	0.50-0.75	45-65%	3-10	5-6	0.10-0.20	700-1,700	10-15
Dispersed Lowrise	>0.90	0.10-0.20	20-30%	3-7m	5-6	0.10-0.20	800-2,000	<10
Lightweight Lowrise	0.30-0.50	1.00-1.50	70-90%	2-4m	4-5	0.10-0.20	600-1,000	<5
Extensive Lowrise	>0.90	<0.25	>80%	3-10m	5	0.15-0.25	1,200-1,500	30-50
Industrial Processing	0.70-0.90	0.2-0.5	45-65	5-10m	5-6	0.12-0.20	1,500-3,000	>200

Ψ_{sky} = Sky View Factor; H:W = building height to width ratio; SF = building surface fraction; Z_H = roughness height; RC = terrain roughness class; μ = thermal admittance; Q_F = anthropogenic heat flux

Table 3: Comparison of ENVI-met initial and final values

ENVI-met model section	Parameter	Initial value	Final value
Main data			
	Domain size	1600m x 1600m	400m x 400m
	Grid size	20m (horizontal) and 3m (vertical)	5m (horizontal) and 3m (vertical)
	Simulated day	30/04/2011	30/04/2011
	Wind speed (m/s)	6.2	4
	Wind direction	270	247
	Roughness length (m)	0.1	0.1
	Initial temperature of atmosphere (K)	283	292.39
	Relative humidity (%)	75	70
Timing			
	Update surface data interval (s)	30	30
	Update wind and turbulence interval (s)	900	900
	Update radiation and shadows interval (s)	600	600
	Update plant data interval (s)	600	600
Lateral Boundary Condition (LBC) types			
	LBC for Temperature and humidity	open	Open
	LBC for Total Kinetic Energy	forced	Open
Building			
	Inside temperature (K)	293	293
	Heat Transmission Walls (W/m^2K)	1.94	1.94
	Heat Transmission Roofs (W/m^2K)	6	2.5
	Albedo walls	0.2	0.6
	Albedo roofs	0.3	0.6
Soil data			
	Initial temp. upper layer (0-20 cm) (K)	293	286
	Initial temp. middle layer (20-50 cm) (K)	293	281
	Initial temp. lower layer (>50 cm) (K)	293	276
	Rel. humidity upper layer (0-20 cm) (K)	50	50
	Rel. humidity middle layer (20-50 cm) (K)	60	60
	Rel. humidity lower layer (>50 cm)	60	70
Timesteps			
	Sun height for switching dt(0)	40	40
	Sun height for switching dt(1)	50	50
	Time step (s) for interval 1 dt(0) (s)	10	10
	Time step (s) for interval 2 dt(1) (s)	5	5
	Time step (s) for interval 3 dt(2) (s)	2	2
Turbulence			
	Turbulence Closure ABL	prognostic	Prognostic

	Turbulence Closure 3D Model	prognostic	Prognostic
	Upper Boundary for e-epsilon	closed	Closed

Table 4: Range of air temperature changes across the simulated domains

	Gla CC-W	Gla CC-E	Paisley	Clyde Gateway	Wishaw	Hamilton
< -1.00						
-1.00 to -0.75				0.2%		
-0.75 to -0.50				0.6%	0.1%	0.4%
-0.50 to -0.25	0.3%		1.8%	1.9%	3.2%	2.6%
-0.25 to 0.00	90.9%	81.0%	94.6%	93.3%	96.6%	95.9%
0.00 to +0.25	8.8%	19.0%	3.1%	4.1%	0.0%	1.1%
+0.25 to +0.50			0.5%			0.1%
+0.50 to +0.75			0.0%			
+0.75 to +1.00						
> +1.00						

Table 5: Predicted Mean Vote (PMV) due to a 20% increase in green cover in 2050

	Gla CC - W	Gla CC - E	Paisley	Clyde Gateway	Wishaw	Hamilton
< -2.0						
-2.0 to -1.5						
-1.5 to -1.0			0.7%			2.0%
-1.0 to -0.5			7.7%	1.0%	1.4%	8.9%
-0.5 to 0.0	4.9%	3.6%	31.1%	20.4%	11.9%	19.1%
0.0 to +0.5	31.8%	35.6%	12.5%	8.4%	9.2%	8.4%
+0.5 to 1.0	15.8%	15.4%	5.8%	3.9%	2.1%	5.4%
+1.0 to +1.5	0.6%	2.1%	15.3%	15.3%	9.6%	18.7%
+1.5 to +2.0	7.0%	6.8%	24.6%	44.2%	57.6%	34.9%
> 2.0	40.0%	36.6%	2.5%	6.8%	8.2%	2.6%

Table 6: 'Best' outcome in Predicted Mean Vote (PMV) in 2050

	Gla CC - W*	Gla CC - E*	Paisley**	Clyde Gateway**	Wishaw**	Hamilton**
< -2.0						
-2.0 to -1.5						
-1.5 to -1.0			1.2%	0.1%		3.3%
-1.0 to -0.5		0.0%	14.4%	8.1%	7.1%	18.2%
-0.5 to 0.0	3.6%	5.2%	42.0%	36.1%	19.3%	29.7%
0.0 to +0.5	48.8%	42.9%	14.5%	6.2%	9.2%	8.0%
+0.5 to 1.0	33.6%	24.7%	6.9%	3.8%	4.0%	9.8%
+1.0 to +1.5	1.2%	1.5%	9.6%	14.7%	13.8%	14.8%
+1.5 to +2.0	3.6%	2.4%	10.6%	30.4%	44.1%	16.0%
> 2.0	9.2%	23.4%	0.8%	0.6%	2.5%	0.2%

Notes:
'Best' PMV outcomes are reached as follows:
* - 20% increase in green cover with Tall buildings (two city centre sites)
** - 100% increase in green cover (all the other four sites)

Table 7: Assumptions and calculation method to derive green infrastructure options for Gla CC-W

	Parameter	Quantity	Remarks
1	Current green cover	3.3%	Measured from GIS maps
2	Total area of the simulation domain	160,000m^2	400m x 400m
3	Available sidewalk	11.15%	Measured from GIS maps (assumes average sidewalk = 2m wide)
4	Standard cover of a street tree	4m^2	
5	Distance between trees	6m	Thus, each tree would 'cover' 12m^2 of sidewalk
6	Total available sidewalk area	17,840m^2	[2] × [3]
7	Possible No of street trees in domain	1,486	[6] ÷ ([5] × 2)
8	Total possible street tree cover	5,947m^2	[7] × [4]
9	Possible street cover as a fraction of total domain area	3.72%	[8] × 100 ÷ [2]
10	Current built cover	52.42%	Measured from GIS maps
11	Usable building cover	40%	Based on a visual inspection of domain area for buildings with flat roof
12	Total usable building area	33,549m^2	[10] × [11] × [2]
13	Total usable building area as a fraction of domain	21%	[12] ÷ [2]
14	Assumed average height of building	12m	Based on visual inspection
15	Total No of block in domain	13	Based on visual inspection
16	Average block size	35m × 30m	
17	Total available Façade area	10,140m^2	[16] × [14] × [15]
18	Total usable façade area as a fraction of domain area	6.34%	[17] × 100 ÷ [2]

Table 8: Alternative approaches to increasing green cover by 20% in Gla. CC-W

Scenario	Permeable vegetated area (m^2)	Street trees (Nos.)	Intensive Roof Garden (m^2)	Extensive Roof Garden (m^2)	Green façade
1. A large park only	1,056				
2. Street trees only		528			
3. 50% of additional greenery in street tree, balance intensive roof garden		264	755		
4. 50% of additional greenery in street tree, balance extensive roof garden		264		1,056	
5. Mix of intensive (50%) and extensive (50%) roof garden			755	1,056	
6. 50% of all 'sun facing' (i.e. South & West) façade covered façade green					1,268

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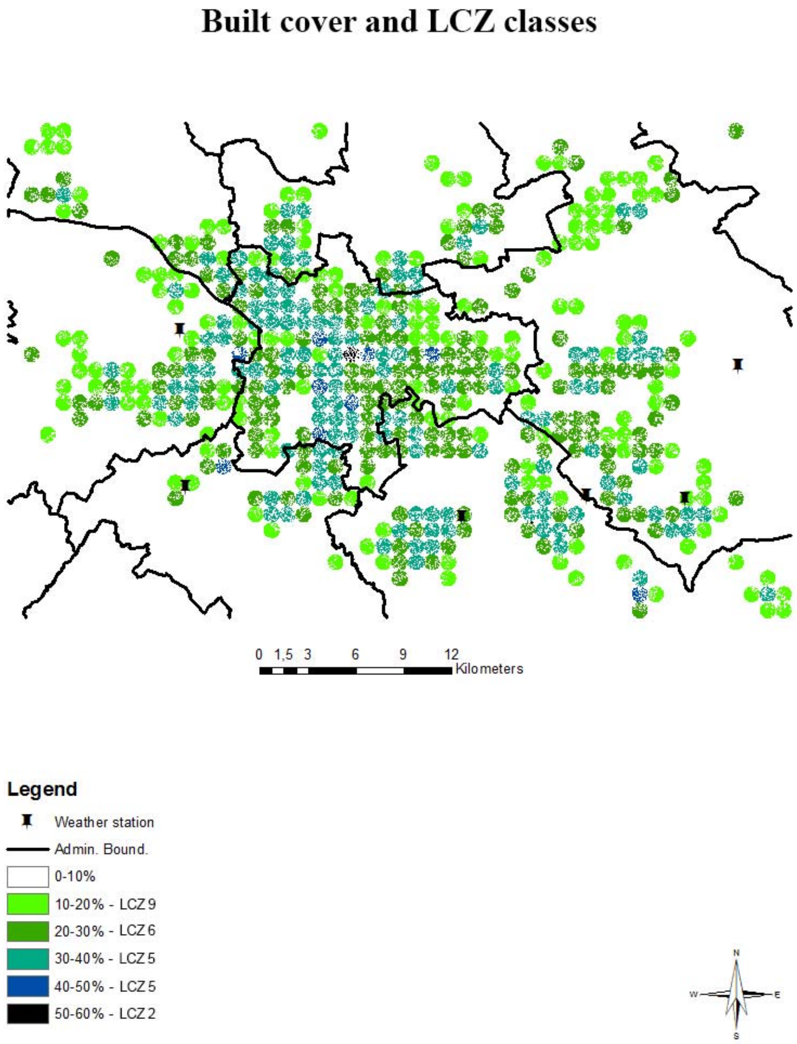

Figure 1: Detailed view of LCZ classes with built cover categories

Figure 2: Selected locations for model simulations

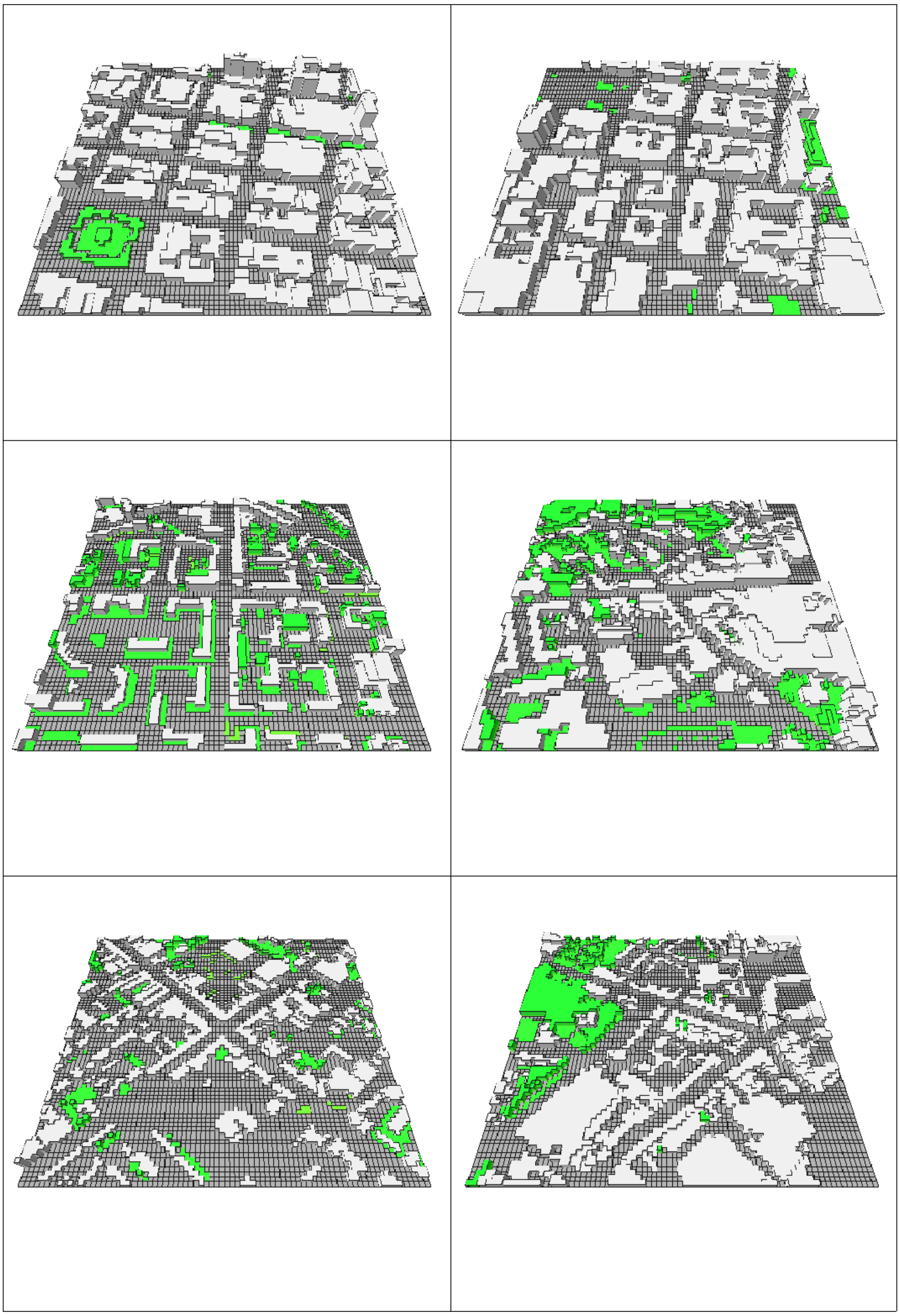

Figure 3: Three dimensional view of selected sites showing the built- and green-cover

Top left: Glasgow City Centre west; Top right: Glasgow City Centre east

Middle left: Glasgow Clyde Gateway; Middle right: Paisley

Bottom left: Wishaw; Bottom right: Hamilton

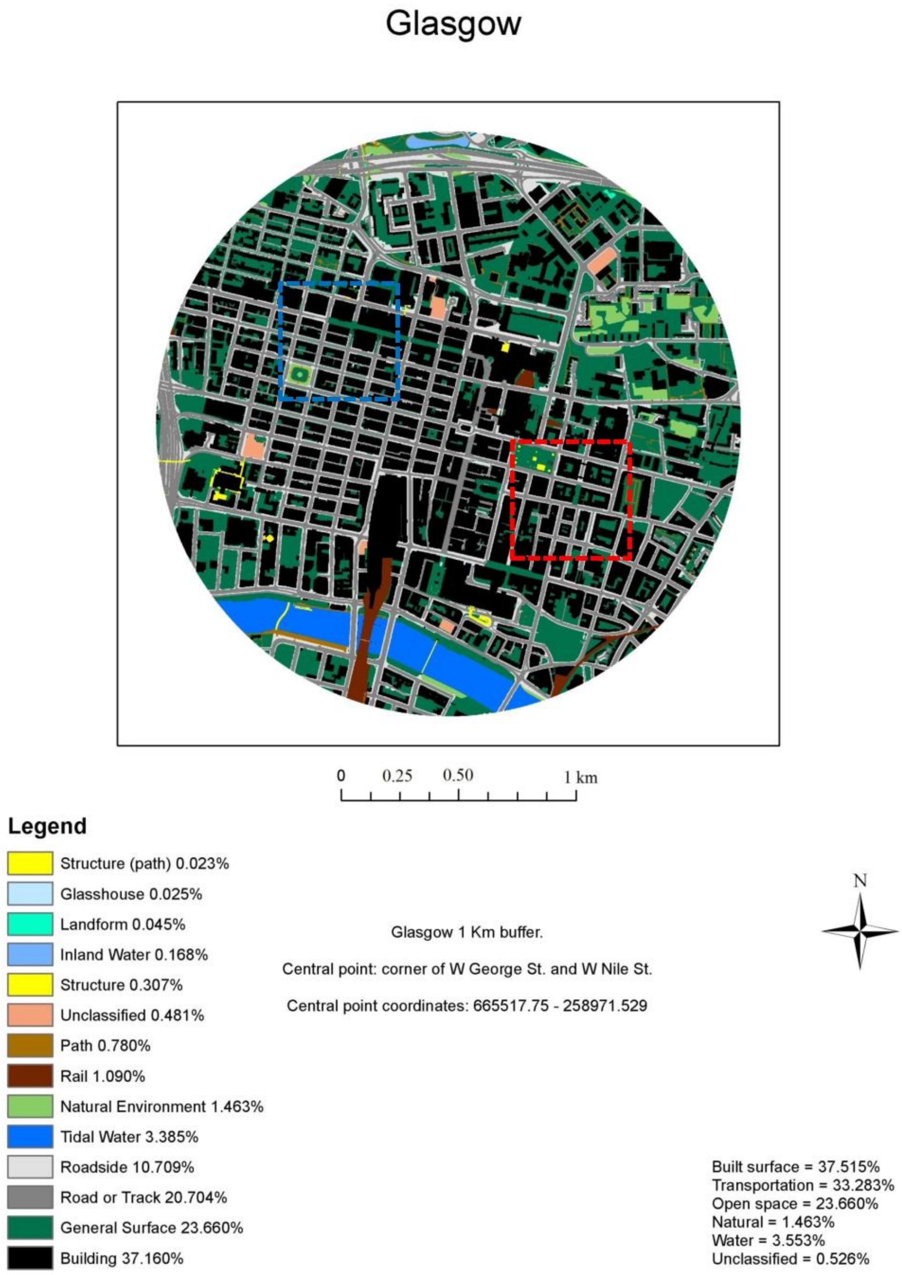

Figure 4: Glasgow city simulation sites (Gla CC-W: blue square; Gla CC-E: red square)

Note: Both Gla CC-W (blue square) and Gla CC-E (red square) are included in this image

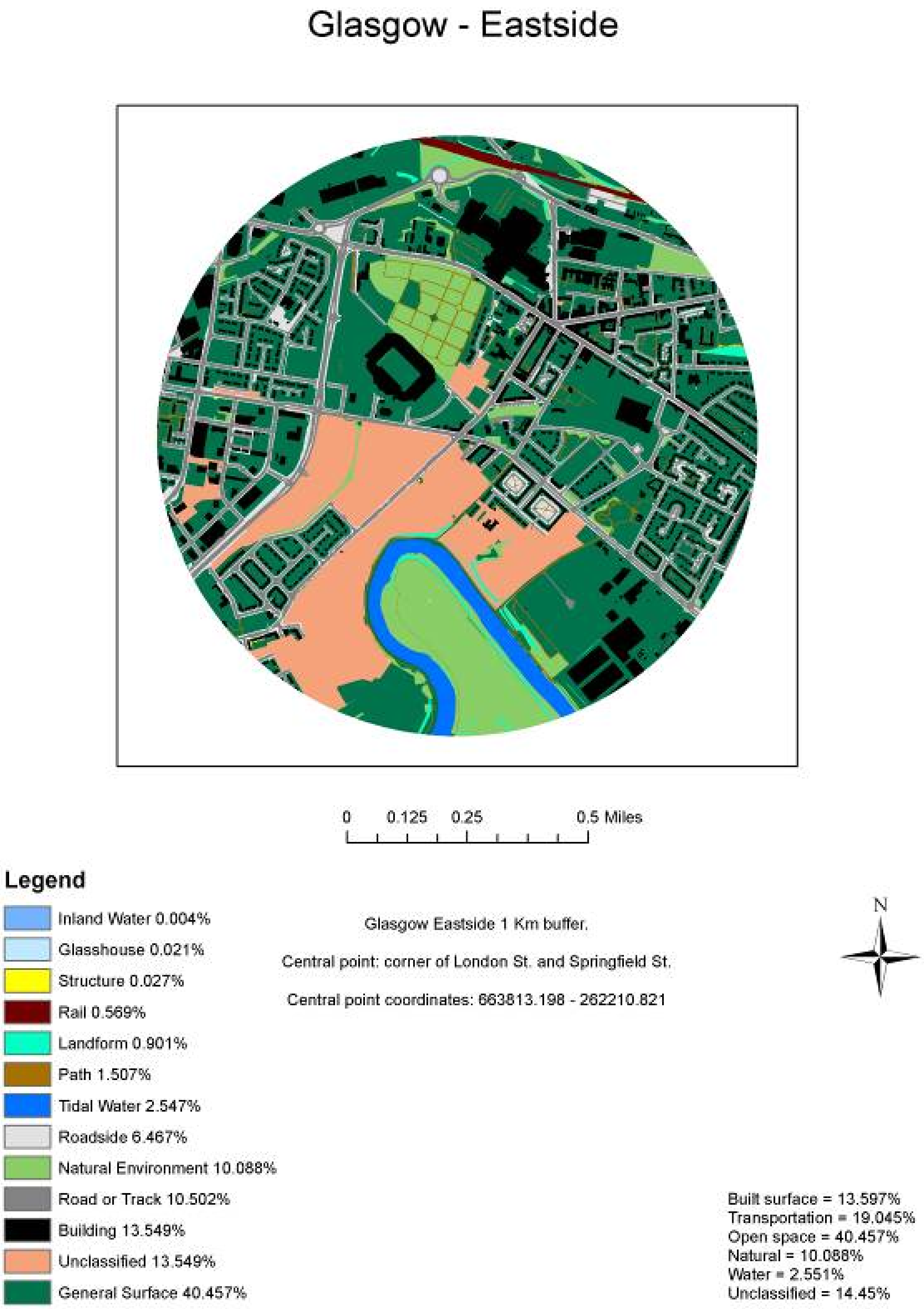

Figure 5: Glasgow Clyde Gateway simulation site

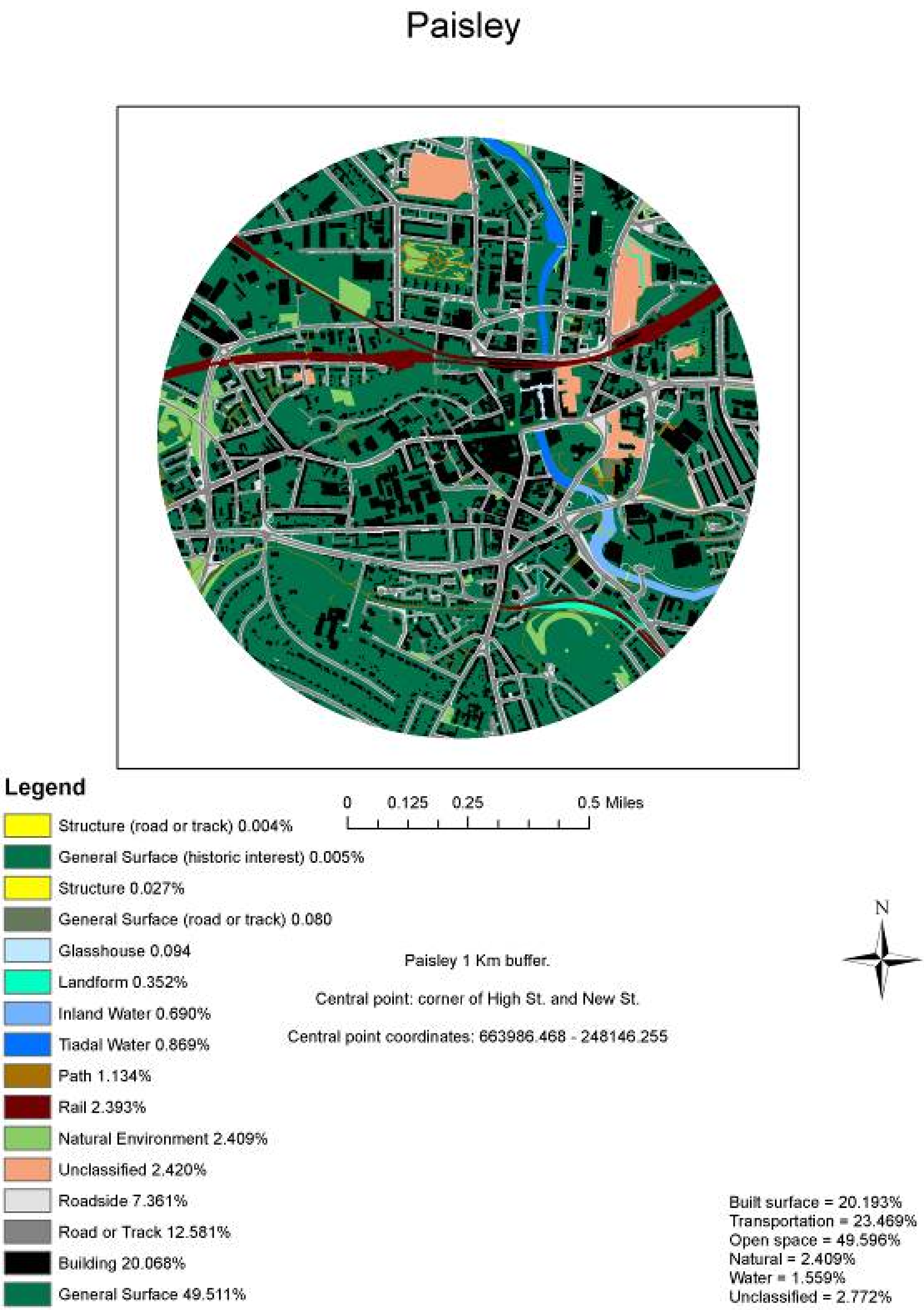

Figure 6: Paisley simulation site

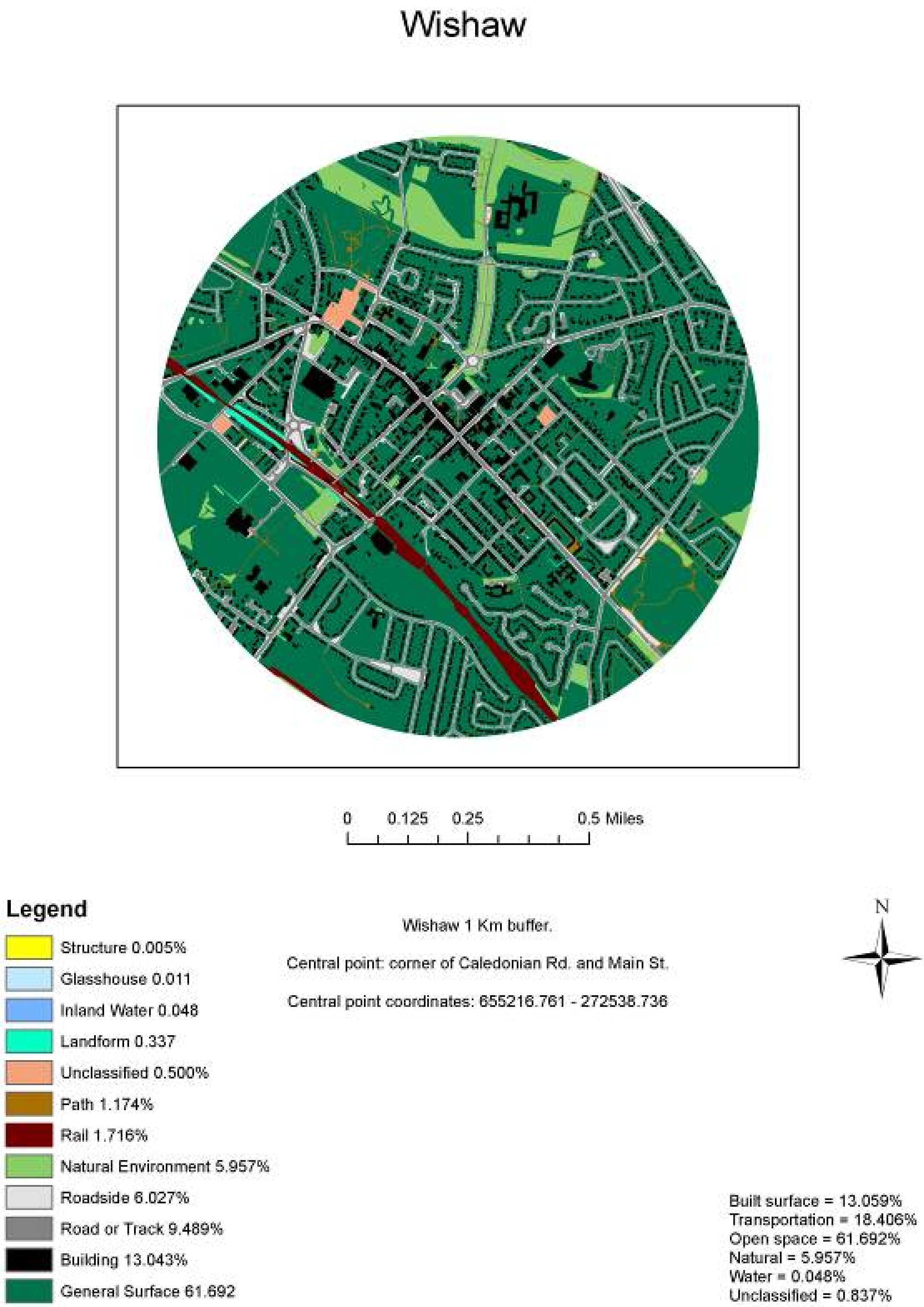

Figure 7: Wishaw simulation site

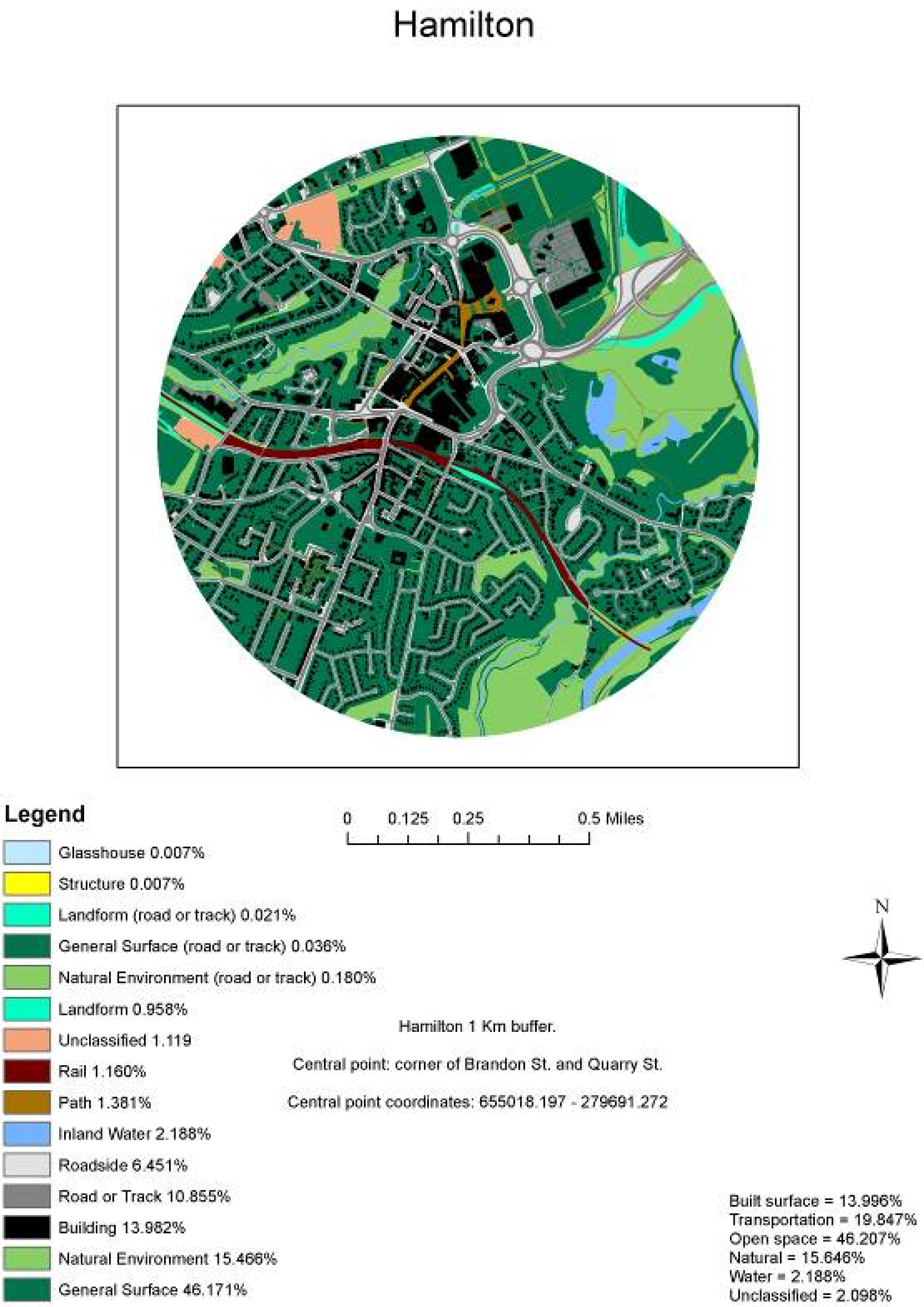

Figure 8: Hamilton simulation site

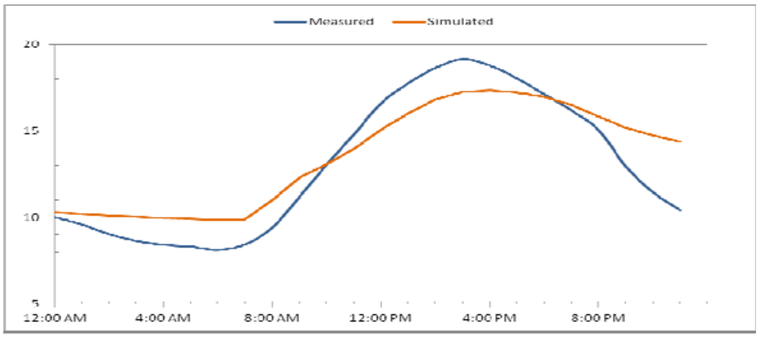

Figure 9: Comparison of measured (GCU Weather Station) and simulated (ENVI-met) temperatures in Glasgow on 30 April 2011

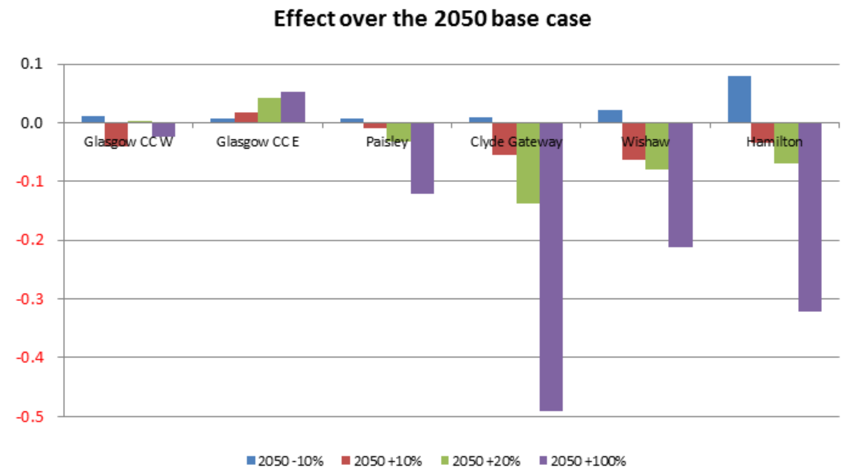

Figure 10: Air temperature effect of green infrastructure – daytime

Notes:
The slight increase in temperature at Glasgow CC-E is an artefact of the location of the changes in green cover relative to the point for which the data is plotted in the figure above. An area averaged change in temperature, as detailed in Table 2 is more representative of the cooling effect in the entire simulated domain area.

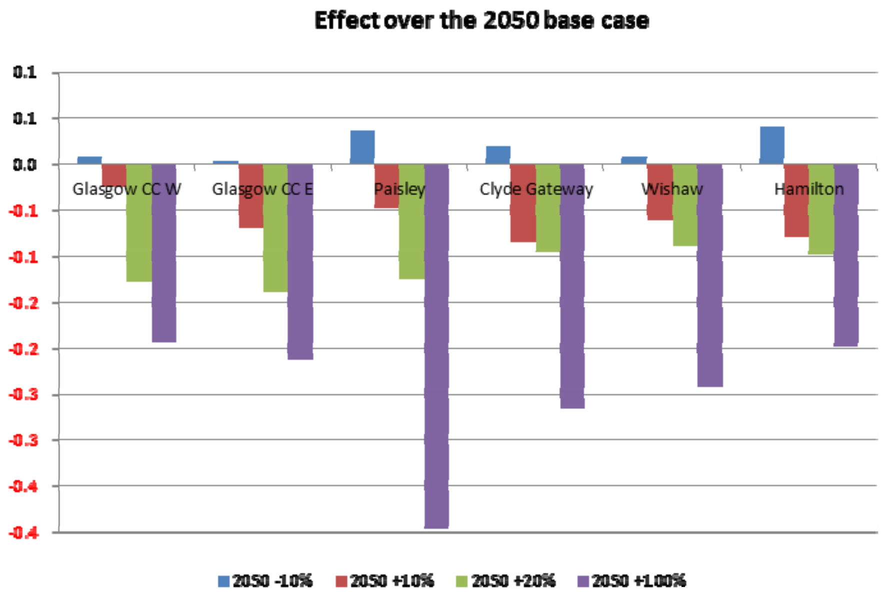

Figure 11: Air temperature effect of green infrastructure – night time

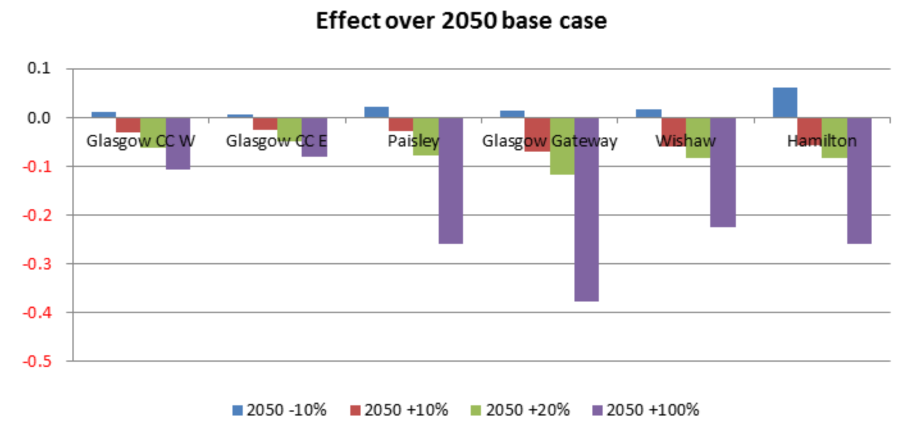

Figure 12: Average daily summertime effects

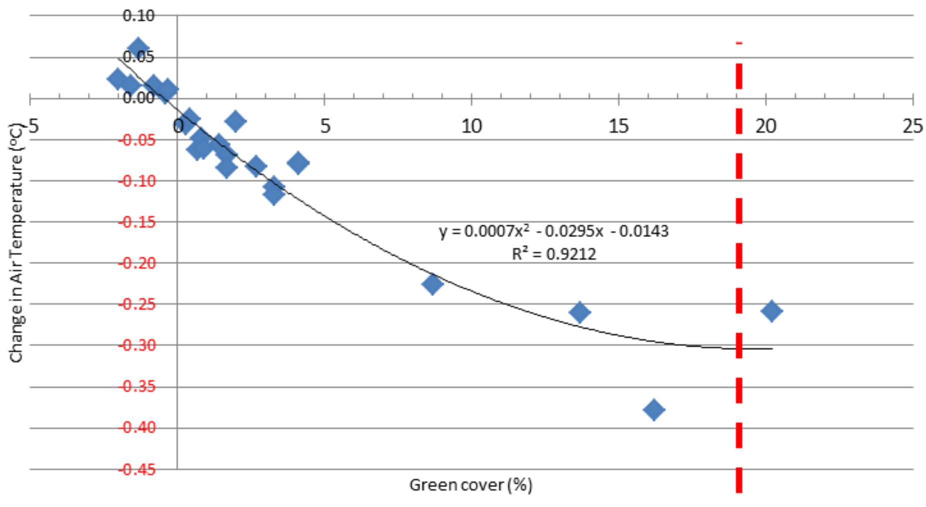

Figure 13: Average daily summertime temperature effect of green cover

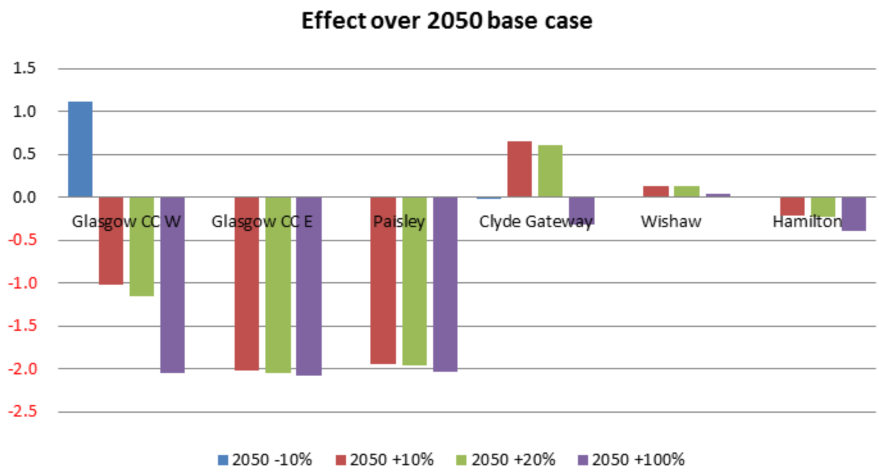

Fig 14: Surface temperature effects at daytime

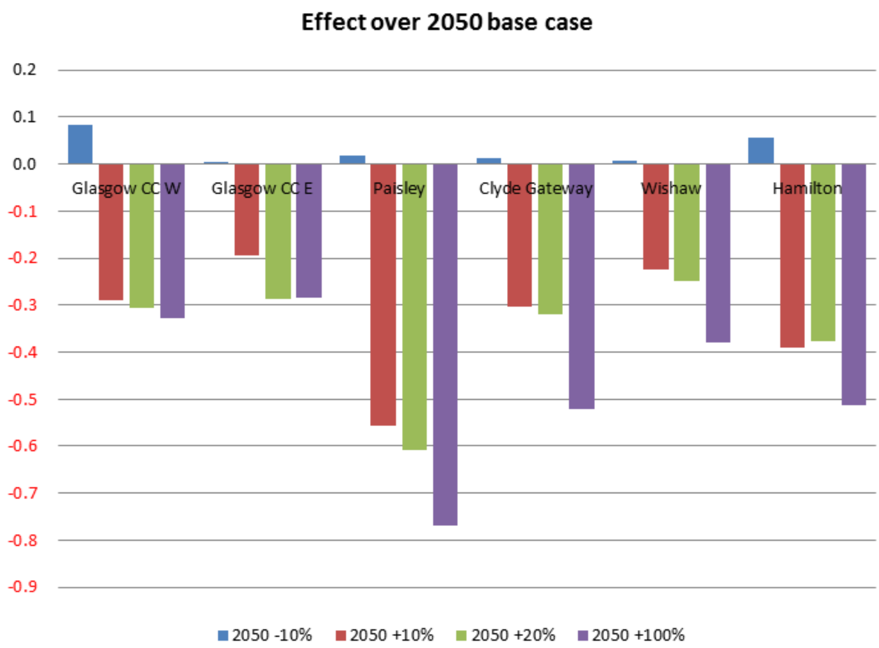

Fig 15: Surface temperature effects at nighttime