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Street trees and Urban Heat Island in Glasgow: Mitigation through the ‘Avenues Programme’

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ABSTRACT

Glasgow, Scotland, is embarking on an ambitious plan to convert all city centre thoroughfares into tree-lined streets (the ‘Avenues Programme’) to make the city centre more people-friendly, attractive, greener, sustainable and economically competitive. While it is well-known that urban green infrastructure (UGI) is a promising strategy to address overheating in urban areas, evidence for the surface temperature, air temperature and thermal comfort effects of street trees is contradictory. In the context of a city-centre-wide ‘Avenues Programme’ in Glasgow, we explore its co-benefits in terms of temperature and thermal comfort. We used a multi-method approach, combining GIS-based spatial analysis with fieldwork, microclimate modelling and statistical analysis to determine the scale of the overheating problem and the likely role of its mitigation based on the ‘Avenues Programme’ case study. We show that the Surface Urban Heat Island (SUHI) differences within the city are of the same magnitude as the urban-rural anomaly and “hot” spots are localized in the city centre area and are clustered in different patterns depending on the severity of background temperatures. Therefore, small, isolated patches of vegetation would not be effective for cooling the clusters of overheated areas. Air temperature showed non-linear relationship with tree canopy cover and the relationship is stronger at medium scale. The ‘Avenues Programme’ as a whole, could eliminate the UHI effect in the city centre, with some tree species completely eliminating the UHI in the city centre. Once complete, the ‘Avenues Programme’ could significantly improve thermal comfort during heatwaves from the current ‘hot’ category to ‘slightly warm’ across the city centre.

1. Introduction

Urban heat islands (UHI) result from the greater trapping of solar radiation in urban areas, pollution acting as a greenhouse, replacement of natural surfaces with artificial materials and the waste heat generated by human activity (Memon et al., 2008; Voogt and Oke, 2003). The synergy between the warming produced by the UHI and projected climate change impacts poses a threat to sustainability and climate adaptation capacity of cities (Emmanuel, 2021). Urban overheating is a concern even in cold climate cities such as Glasgow, Scotland, where thermal adaptation of local population to cooler climates (Kruger et al., 2013) and climate change (Kendon et al., 2019) make it particularly problematic.

Urban green infrastructure (UGI), i.e., network of green spaces (parks, street trees, green roofs etc.) is a promising strategy to address overheating in urban areas as vegetation provides cooling through evapotranspiration and shading (European Commission, 2013; Winbourne et al., 2020). Additionally, UGI offers multiple environmental

and social benefits and can be retrofitted in the existing built environment (European Commission, 2013). In Scotland, role of UGI in regulating urban climate is well recognized within research circles, local authorities and outlined across several policies (Scottish Government, 2004, 2008, 2014a, 2014b). However, integration of the UGI into urban planning practices for the purpose of UHI mitigation and climate adaptation remains insufficient (Emmanuel and Loconsole, 2015; Matthews et al., 2015). The reasons behind this research-policy-practice disconnection are related to the overload of theoretical research without providing clear recommendations, as well as lack of comparable information and realistic case studies to demonstrate the cooling potential of UGI types in the local context (Monteiro et al., 2019). Additionally, the risks of the UHI are often overlooked in the context of climate change.

Glasgow is currently undertaking a major programme of converting several city centre streets into ‘Avenues’ in a bid to transform the city centre streetscape and public realm to be “more people-friendly, attractive, greener, sustainable and economically competitive” (GCC,

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2022). While the focus of this major investment programme (ten-year programme with a total investment of £136 million in 2022) is to create an integrated network of continuous pedestrian and cycle routes across the city centre, we explore the level of urban heat risk in the city centre and the likely local cooling effects that 'Avenues' programme may provide. In order to contextualise the scale of the overheating we first investigate seasonal and spatial patterns of the surface UHI (SUHI) at the city-scale and identify areas of potential overheating. We then assess the relationship between the summertime SUHI and present citywide vegetation cover with respect to UGI types. Finally, we investigate the UHI mitigation potential and outdoor comfort implications of the Glasgow city centre 'Avenues Programme'. We provide empirical evidence for the effectiveness of the strategy to address local "hot" spots in the city centre and alternative ways to enhance local cooling.

2. Background

2.1. Cooling effects of urban greening in a temperate climate

The cooling effect of UGI of different types and shapes has been widely studied (Santamouris, 2014; Lobaccaro & Acero, 2015; Myint et al., 2013; Aram, et al., 2019). While there are other approaches to city centre cooling in temperate climates (such as the modification or changing urban geometry) and these may be more impactful than vegetation (Lai et al., 2019), such approaches are rarely possible in mature cities and built-up downtown areas and will be more cost intensive in comparison with UGI interventions.

Urban parks provide substantial cooling in temperate cities. A study in London found that eight city centre parks were up to 3.8°C cooler than the surrounding built-up areas (Vaz Monteiro, et al., 2016). Similar findings were reported from Leipzig (Germany), where greenspaces provided 3.0°C cooling, extending up to 470 m (Jaganmohan, et al., 2016). Urban parks have more cooling and thermal comfort regulation potential than small green spaces (Givoni, 1991), though cities clearly face spatial and economic barriers to achieving dense network of greenspaces. Emmanuel and Loconsole (2015) estimated that 20% increase in green cover, provided by combination of different UGI types, could counterbalance the warming expected by 2050 in Glasgow (UK) by 30% and reduce local surface temperatures by 2°C. Although such estimates are promising, not all vegetation is equally effective in mitigating urban temperatures (Norton et al., 2013).

At the same time, UGI in heavily built-up city centres experience multiple stresses due to urban density and impervious surfaces (Majekodunmi et al., 2020) and the actual cooling effect of UGI may not reach its full potential. The impervious surface cover in the immediate vicinity of UGI appears to exert more influence on microclimate while the larger-scale forested canopy is more important in explaining temperature fluctuations at the city scale (Howe et al., 2017). The temperature effects of UGI are further modulated by the type of trees, age of trees and their locations (Ren et al., 2023), with more alien species adapted to warmer climates surviving better in city centres (Geron et al., 2022). A warming climate could enhance the survivability of alien species across a broader area of the city.

Furthermore, the shielded environments prevalent in city centres in temperate climates (due to buildings blocking the view to open sky) influences the leaf and development traits of UGI (Geron et al., 2022).

2.2. Street trees and urban heat island

UGI is a promising option to mitigate urban heat stress. Taleghani, (2018) demonstrated that although high albedo materials decrease the surface temperatures, they increase heat re-radiation to the pedestrians; therefore, the UGI would be a more preferable design option for improving urban thermal environment. While parks and urban forests are acknowledged for temperature regulation due to the "Park Cool Island" effect (Spronken-Smith and Oke, 1998), cities face spatial and

economic barriers to densifying network of greenspaces. Consequently, integrating vegetation into the city fabric at finer scales (such as street trees) is more feasible and will ensure thermal comfort at the scale of the pedestrians' everyday activities.

Several GIS-based studies assessed the cooling impacts of green areas by exploring relationships between the UHI and Normalised Difference Vegetation (NDVI) index (Farina, 2012; Guha et al. 2019), thus ignoring the diversity of the UGI. Balany et al., (2020) identified that trees are the most investigated and suggested UHI mitigation strategy, followed by grass and green roofs. Cooling benefits of the UGI have been mostly shown by empirical and microclimate simulation studies, many of which focused on a single measure or generalized green cover. Multiple works highlighted the role of trees in moderating air temperatures (Jochner et al., 2013, Tsoka, 2017; Makido et al., 2019, Porangaba et al., 2021) and thermal comfort (Duarte et al., 2015, Zölch et al., 2016; Teshnehdel et al., 2020). Some studies demonstrated the effects of grass and shrubs on surface temperatures (Zhang, 2020) and of green roofs on mean daily air temperatures (Tsoka et al., 2018). Although these greening strategies have less control over thermal comfort compared to trees (Lobaccaro and Acero, 2015; Zölch et al. 2016) they require less space and are easier to maintain, thus, could be a good greening approach if space or finance is limited.

2.3. Avenues approach to urban improvement

Avenue (a tree-lined street) has been an important element in city centres since ancient times but became central to urban improvement since the renaissance period in Europe and colonial times in the new world. These include, processional avenues of Rome to link the great Basilicas and other strategic points in late 16th to early 17th Centuries (Ago, 2018); avenues as ventilation corridors in late 18th – early 19th Century Warsaw, Poland (Osinska-Skotak and Zawalich, 2016); as recreational axes in several Greek cities (Bakogiannis et al., 2019); Berlin in the 17th century (Lawrence, 2008) and as green tunnels in Porto Alegre, Brazil in early 20th Century (Salvi et al., 2011).

In contemporary urban planning Avenues are seen as anchors of urban regeneration (Beletzky, 2017). Their appeal to tourism and recreation (Beletzky, 2017), urban revitalisation (Sanchez, 2018), urban iconography (Golan, 2015), walkability (Zaninović and Scitaroci, 2012), public health (Venegas-Sanchez et al., 2013) and biodiversity improvement (Liu and Slik, 2022) have been extensively studied.

Perhaps the most commonly studied environmental aspect of Avenues is their effect on air quality. Gromke and Ruck (2012) found that, compared to tree-free street canyons, Avenues had higher pollutant concentrations and reduced air ventilation. This effect depends on wind direction, with increases in wall-average and wall-maximum concentrations at the leeward canyon wall and decreases in wall-average concentrations at the windward for perpendicular wind directions with the strongest effects for oblique wind directions. Similarly, unfavourable effects of trees on pollutant dispersion and natural ventilation were found by Gromke, (2011) and Santiago et al., (2022). Trees in the sidewalks act as a barrier for pollutants emitted outside, specifically for a 45 degrees wind direction. The interaction between avenue trees and air quality is highly complex and depends on vegetation type and density, meteorological conditions, street geometry, pollutant characteristics and emission rates (Buccolieri et al., 2019). Furthermore, it is important to consider the wider (outside the Avenue) air quality effects of street trees since there is conflicting evidence as to their positive (or negative) effects (Gromke and Blocken, 2015).

While there are many studies on the cooling effects of UGI in general, the specific effects of Avenue trees are not clear. Reviewing several studies on the thermal effects of street trees, Buccolieri et al., (2019) found that the effects were locally restricted to the immediate vicinity of the vegetation and to the street canyon itself. Chen et al., (2021) found that street trees could have a positive or negative thermal effect depending on the vegetation type, crown size and density and tree

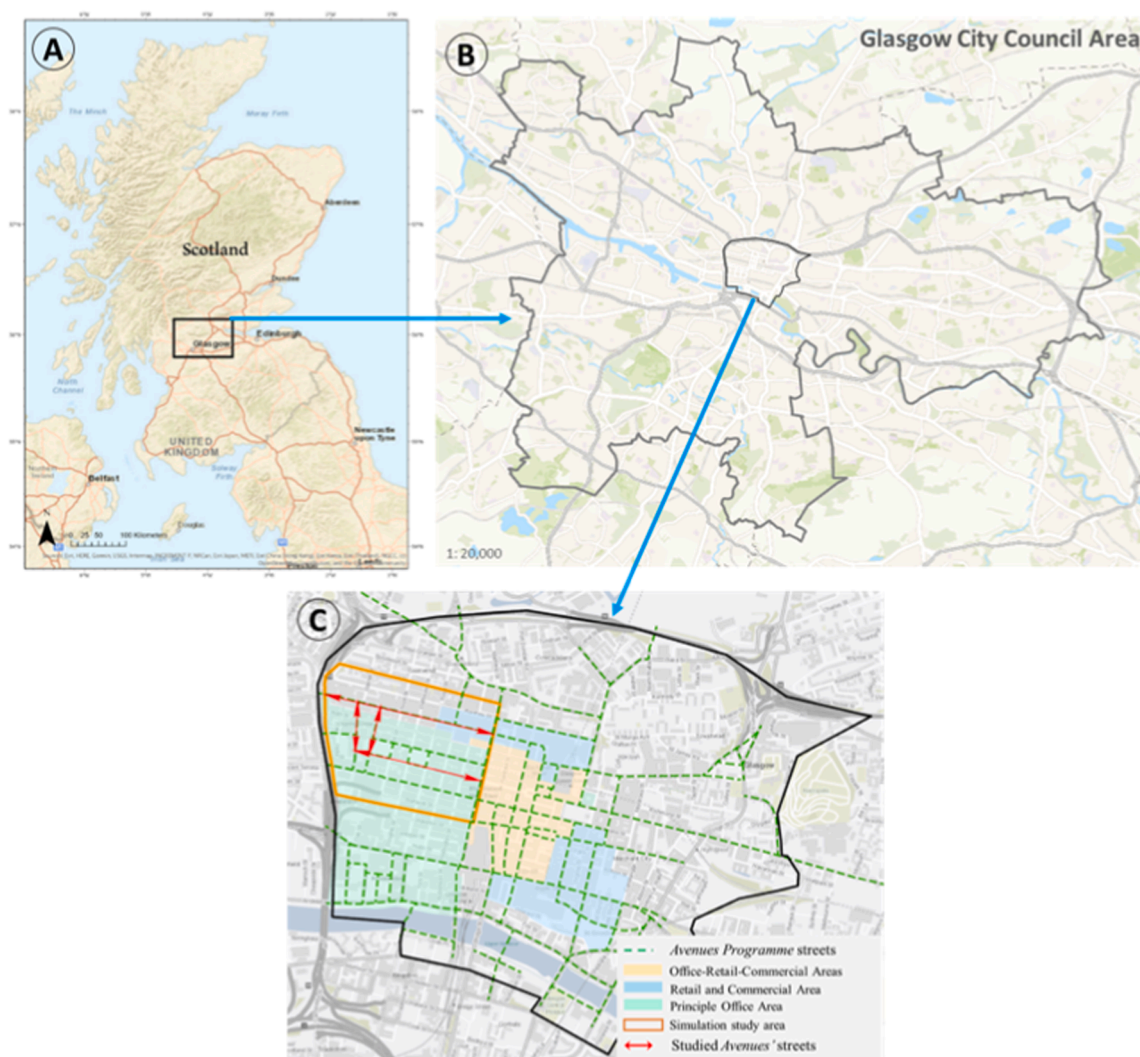


Fig. 1. Glasgow context and the 'Avenues Programme' area; (A) Glasgow City Council Area within Scotland and rest of the UK; (B) Glasgow City Council area with city centre outlined; (C) the 'Avenues Programme' overview with city centre outline

Source: (a) AND (B) – own image obtained with arcgis pro; (C) – based on Glasgow 'Avenues Programme' website (<https://glasgowgis.maps.arcgis.com/apps/webappviewer/index.html?id=e868fa1bfc8b4558a1aca7c374151b6d>); (C) – city centre land use obtained from the interactive map for Development Plan: SG4 Network Of Centres (<https://glasgowgis.maps.arcgis.com/apps/webappviewer/index.html?id=e868fa1bfc8b4558a1aca7c374151b6d>).

placement intervals.

Additionally, there are specific knowledge gaps in Scotland of the UHI mitigation benefits of street trees in dense built environments. This is despite the importance of greenspaces being acknowledged in Scottish policy in terms of amenity value, flood management, air purification (Scottish Government, 2008, 2014a, 2014b), etc. The UHI mitigation benefit, especially at the street scale, is not seen as a priority in the design and management of UGI (Monteiro et al., 2019). Given the imminent deployment of street trees at a large scale throughout the city of Glasgow, the 'Avenues Programme' as detailed below, provides a good case study to evidence the cooling potential of street trees in the local conditions of Glasgow and support planners in their decision-making process.

3. Methodology

3.1. Study area

Glasgow (55.860916 N – 4.251433 W) was selected as a geographical focus of this study due to the emerging risks of overheating (GCC, 2021) and the city's major investment in the 'Avenues

Programme',¹ a quality place-making scheme that will transform 21 key streets ('Avenues') in Glasgow city centre by introducing green and SMART infrastructure. Previous research indicated that, even though urban growth has subsided in Glasgow, the observed UHI is already of the same magnitude as temperature increase expected due to the climate warming by 2050 (Emmanuel and Krüger, 2012; Krüger et al., 2013). As climate impacts intensify, green infrastructure can be a viable strategy to moderate the local overheating (Emmanuel and Loconsole, 2015), but the likely effects of the large urban improvement programme of 'Avenues' is unknown. Although UHI mitigation and climate adaptation are not the primary aims of the Glasgow 'Avenues Programme', proposed UGI might affect the thermal environment of the retrofitted streets and provide a valuable case study. Given that all city centre thoroughfares will eventually be converted into 'Avenues' by 2028, we chose to investigate the impacts of the programme for four major city centre streets: Sauchiehall Street, Holland Street, Elmbank Street and St Vincent Street. Our parameters of focus are SUHI, local microclimate and thermal comfort. The full extent of the 'Avenues Programme' in the

¹ <https://www.glasgow.gov.uk/avenues>

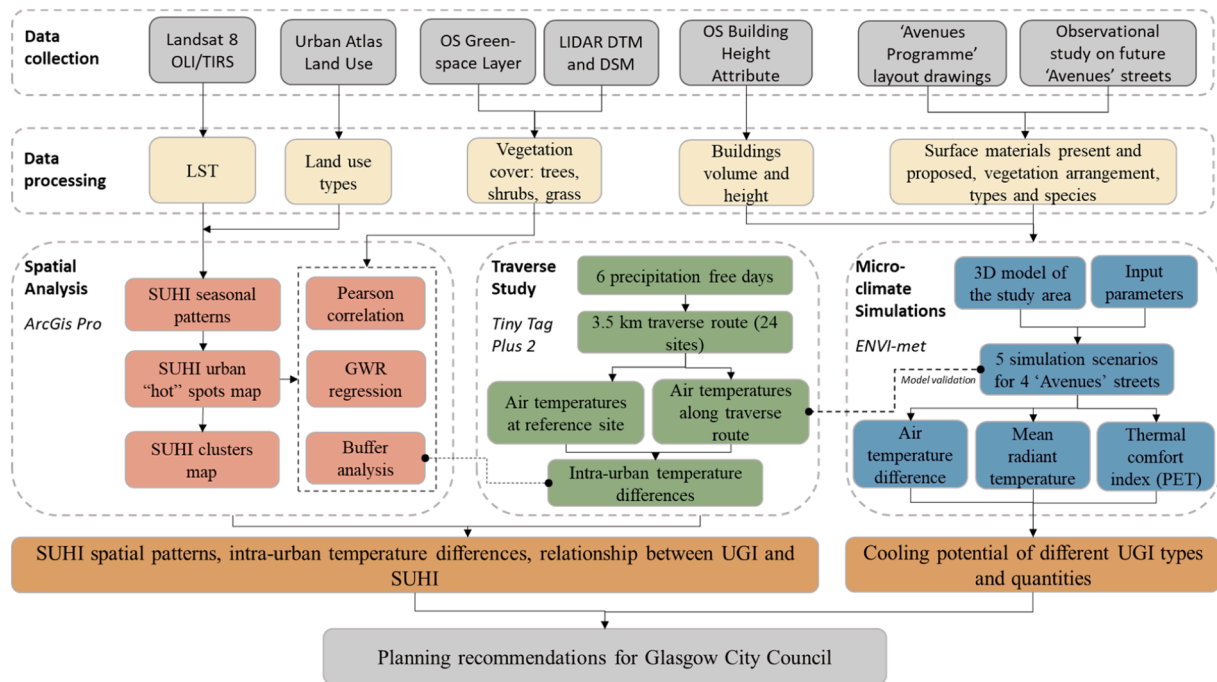


Fig. 2. Study design and major research steps.

context of the city centre of Glasgow is shown in Fig. 1.

3.2. Research framework

A multi-method approach, combining GIS-based spatial analysis with fieldwork, microclimate modelling and statistical analysis, as demonstrated by Fig. 2 (Ananyeva, 2021), was used to investigate Surface Urban Heat Island (SUHI) patterns and their interaction with UGI across three spatial scales: city-level, local-scale – city centre level, and microscale – individual streets.

ArcGIS Pro software package was applied to retrieve and map SUHI estimates, analyse SUHI spatial patterns at the city-level and establish relationship between SUHI and UGI distribution, taking into account UGI types. This helped to identify summertime overheating areas and delineate the study area for the fieldwork. A traverse study was undertaken to explore the intra-urban temperature variations at local scale – within Glasgow City Centre. This was followed by the analysis of the relationship between observed atmospheric temperatures and tree canopy cover. Additionally, air temperature data and observations on the UGI types, arrangements and distribution collected during the fieldwork were further used for validation of the microclimate simulation model and development of the simulation scenarios. Simulations were performed to investigate the implications of the Glasgow City Centre overheating patterns on human receptors at the scale of individual streets and understand the cooling potential that can be delivered by the 'Avenues Programme'. ENVI-met v.4.4.5 model was used to carry out the simulations. Model outputs were further finalized using LEONARDO and BIO-met v.4.4.5 post-processing tools. All data management and analysis were performed with IBM SPSS Statistics 26 and Microsoft Excel.

A summary of the data used for this study, followed by short description of its application, is given in Table 1.

The major limitations of this study relate to temporal constraints of the remote sensing data and the lack of high-quality spatial data on UGI with differentiation by type. However, an adequate number of remotely sensed scenes were available, even if these do not cover all seasons and a physically verified UGI data, albeit somewhat older (2015) was used to delineate UGI cover.

3.3. Citywide analysis of the spatiotemporal patterns of UHI

Fig. 3 highlights major procedures carried out to retrieve and map Surface Urban Heat Islands (SUHIs) estimates and analyse SUHI spatial patterns at the city-level. Spatial analysis was carried with ArcGIS Pro software package, while SPSS and Microsoft Excel were applied for all statistical tests.

3.3.1. Land surface temperatures retrieval

Land surface temperatures (LSTs) were used to explore seasonal and spatial variation of UHI within Glasgow City area. Eight cloud-free (< 10%) Landsat 8 OLI/TIRS remote sensing datasets corresponding to each season in three consecutive years (2018–2020) were downloaded from USGS EarthExplorer data portal² and further processed to retrieve LSTs following the methodology by Avdan and Jovanovska (2016). Winter season was represented by two images only (2018 and 2019), as there were no cloud-free data available for 2020. Table 2 provides specification of multirate Landsat OLI/TIRS images. All images had a standard resolution of 30 m.

In literature, the land surface temperatures (LST) obtained from remote sensing data are widely used as a proxy of the UHI phenomenon (Guha et al., 2019; Abulibdeh, 2021). However, there are limitations to the use of remotely-sensed LST in a study that also uses Air Temperature (AT) at the local scale. Comparing the remotely sensed LST with ground-based AT measurements across the globe, Zhang et al., (2020) found that the correlation between the two are location-specific. In the UK, the correlation is moderate, with a higher correlation during daytime (in contrast, LST vs AT are weakly correlated in the tropics where cloud contamination is a significant influencing factor). Additionally, the 30 m resolution of the LST further limits its use at the street scale. In this study LST approach was used to understand the distribution and pattern of the SUHI across the city of Glasgow and verify whether a "hot" spot exists in the general area of the 'Avenues' programme and therefore, a 30 m resolution is suitable for the purposes of the present study.

² <https://earthexplorer.usgs.gov>

Table 1
Summary of the data used in the study.

Research stage	Data	Sources	Application
Spatial Analysis and Modeling	Landsat 8 OLI and TIRS satellite images	USGS, n.d.	LST, SUHI retrieval, analysis of the urban SUHI “hot” spots
	LIDAR DSM and DTM	UBDC, 2019	Differentiation of vegetation types based on height
	OS Mastermap Greenspace Layer	Ordnance Survey GB, 2020	Analysis of relationships between SUHI and UGI cover in general and by types
	Glasgow Electoral Wards Glasgow Intermediate Zone Boundaries 2011 (data zones)	National records of Scotland, 2020 Scottish Government SpatialData.gov.scot, 2021	Auxiliary data for SUHI analysis Auxiliary data for LST, SUHI, greenspace zonal analysis
Fieldwork	Air temperature measurements	Obtained from traverse study conducted by authors (May 2021)	Analysis of intra-urban temperature variations in relation to tree cover ENVI-met model setup and validation
	Observations on tree types and arrangement on Sauchiehall St.	Observational study conducted by authors (May 2021)	Streets’ design and UGI arrangements inputs for the ENVI-met microclimate simulation scenarios
Microclimate Simulations	OS Mastermap Topography Layer	Ordnance Survey, 2020	Development of the modelling domain for microclimate simulations in ENVI-met environment
	OS Buildings Heights	Ordnance Survey GB, 2019	Cross-checking of buildings’ height.
	LIDAR DSM and DTM Met Office hourly observations data 2018–2021	UBDC, 2019 UBDC, 2021	Meteorological inputs for microclimate simulations
	Design proposals for the Holland St. and Elmbank St.	Public Consultation Documentation. Glasgow City Council, 2019	Streets’ design and UGI arrangements inputs for microclimate simulation scenarios

3.3.2. Quantification of the surface UHI intensities

SUHI intensities were obtained with ArcGIS Pro raster statistics and calculator tools using Eq. 1 (Xian et al., 2021):

$$SUHI = \Delta LST = LST(i, urban) - \overline{LST}_{rural} \quad (1)$$

where SUHI – surface UHI, ΔLST – temperature difference, $LST(i, urban)$ – LST of i^{th} urban pixel, \overline{LST}_{rural} – mean LST of pixels corresponding to pastures and arable lands within 3-km non-urban buffer.

High resolution land cover data used in the analysis was downloaded as the Urban Atlas 2018 geo-package from the website of the Copernicus Land Monitoring Service³.

Distribution of the mean summertime SUHIs, retrieved as an average of pixel-based values, was described in relation to 13 land use categories and across 23 Glasgow City wards (National Records of Scotland, 2020).

3.3.3. Analysis of urban “hot” spots and SUHI clusters

Analysis of the intra-urban temperature variations was undertaken to identify SUHI urban “hot” spots, areas with higher-than-average temperatures within SUHI zones. Even though LST and SUHI patterns were investigated for all seasons, further analysis of urban “hot” spots and interactions with vegetation cover was performed only for the mean summertime SUHI (mean of 2018–2020) and 25 June 2018, the hottest day just before the 2018 heatwave (further referred as a heatwave period). Even though 28 June 2018 was in fact the hottest day during the 2018 heatwave in Scotland, Landsat 8 OLI/TIRS satellite images for this date or any other heatwave dates were not available for the Glasgow area.

SUHI urban “hot” spots were defined with consideration of the intra-urban LST differences by following Eq. 2 (Ma et al., 2010; Guha et al., 2019):

$$LST > \mu + 0.5 \times \delta \quad (2)$$

where μ and δ are the mean and standard deviation of the LST in the study area, respectively.

Further, Global Moran’s I spatial autocorrelation was used to estimate the degree of spatial clustering of the mapped summertime SUHI “hot” spots and SUHI observed during the 2018 heatwave period. Analysis was carried out at the data zones level, geographical units for analysis of small area statistics (Scottish Government, 2021a 2021b), using ArcGIS Pro Spatial Statistics toolbox. The Global Moran’s I tool assesses the pattern of a dataset spatially and determines if it is dispersed, clustered, or random based on the locations and values of the feature. The basic assumption for the Global Moran’s I statistic is that the data values are independent and randomly arranged in the geographical space. The approach to interpretation of the Global Moran’s I analysis is shown in Table 3.

3.3.4. SUHI – UGI relationship analysis

Pearson correlation analysis was performed between SUHI and UGI data for 746 data zones. Data zones are the key geographical units for analysis of small area statistics (Scottish Government, 2021a 2021b). A shapefile of the Glasgow Intermediate Zone boundaries (data zones) was used to calculate the mean SUHI and percentage of the green cover by type in each data zone. SUHI data corresponded to the heatwave period (25 June 2018) and was obtained following the methodology as outlined in Section 2.3.3. UGI information was obtained from OS Mastermap Layer (Ordnance Survey, 2020) and further classified into grass, shrubs and trees using Digital Surface Model retrieved from the LIDAR data, which was provided by the Urban Big Data Centre at the University of Glasgow (UBDC, 2021). Pearson correlation analysis was performed for 746 Glasgow data zones.

To explore the spatial variation of relationship between SUHI and UGI (all types combined), GIS-based Geographically Weighted Regression (GWR) analysis was performed with the ArcGIS Pro software. GWR is an alternative to conventional regression approach, which can model the spatial variation between variables (Zhao, et al., 2018; Wang, et al., 2020). Analysis was performed at data zones level. Local R^2 coefficient was used to interpret the results.

3.4. Traverse study

Air temperatures were collected from 24 locations along a 3.5 km transect crossing Glasgow City Centre in W – E direction (Fig. 4). Sampling was undertaken twice a day (14:00 – 15:00 and 19:00 – 21:00) on 6 precipitation free days in May 2021 using Tinytag Plus 2 (TGP-4500) air temperature data logger. The traverse study protocol suggested by Maharroof et al., (2020) was adopted and followed.

The traverse was carried out by a walking person using the data-logger covered with naturally ventilated sun-protection shield and fixed to a backpack at 1.5 m height. Fig. 4 indicates the route of the traverse

³ <https://land.copernicus.eu>

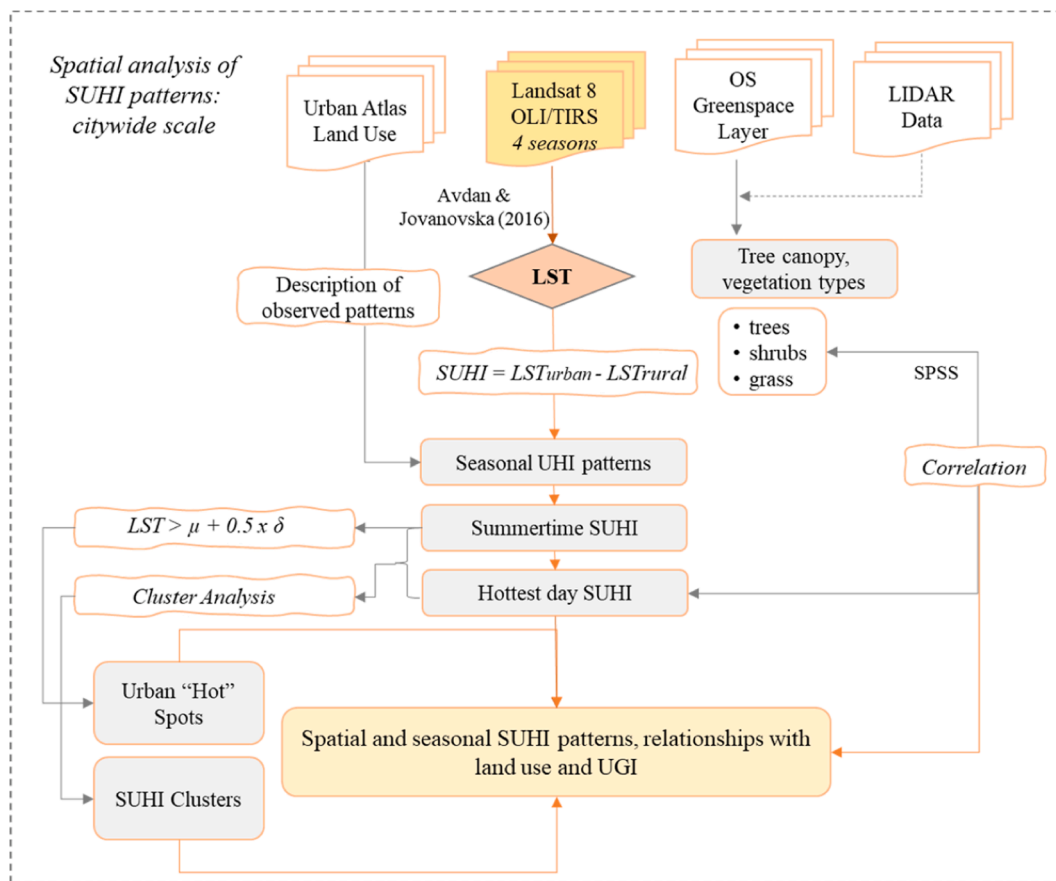


Fig. 3. Steps to delineate citywide surface UHI (SUHI) patterns and relationships.

Table 2
Specification of multirate Landsat 8 OLI/TIRS satellite images.

Date of acquisition	Time	Cloud cover (%)	Sun elevation (deg)	Sun azimuth (deg)
09-Dec-2018	11:21:59	0.98	10.5121	168.0606
24-May-2018	11:14:49	9.80	53.3261	157.4328
25-Jun-2018	11:14:55	0.28	55.5159	154.2647
15-Oct-2018	11:15:45	9.62	24.8387	167.8445
11-Feb-2019	11:21:51	0.99	18.3906	161.3048
31-Mar-2019	11:21:38	9.80	36.6908	160.1299
28-Jun-2019	11:15:48	0.49	55.4304	154.4005
02-Oct-2019	11:16:16	0.90	29.7315	166.2653
18-Apr-2020	11:21:40	9.03	43.7337	159.9460
08-Aug-2020	11:22:04	9.90	48.1825	156.5307
28-Nov-2020	11:22:26	9.80	12.0379	168.9707

Table 3
Interpretation of the Global Moran's I analysis.

Moran's I output values	Interpretation
$I = +1$	The pattern observed is clustered spatially
$I = -1$	Dataset is scattered or dispersed spatially
$I = 0$ or close to 0	Absence of autocorrelation
$p > 0.05$	Basic assumption is accepted - data values are randomly spread out spatially
$p < 0.05$, z-score < 0	Basic assumption is rejected - high and low values in the dataset are dispersed spatially
$p < 0.05$, z-score > 0	Basic assumption is rejected - high and/or low data are spatially clustered in the geographical space

and the points on the route indicate locations where the data was collected. Fig. 5 shows the typical geometry of the streets and air temperature variations within study area on 31 May 2021, the hottest day of the fieldwork.

The average air temperatures were obtained from 5-min sampling datasets gathered in each location at 2 s intervals. To enable comparison, measurements were time corrected and converted into temperature differences relative to data obtained from the reference sensor, which was mounted in Stevenson type screen to the streetlamp pole at 2.5 m height at Glasgow Caledonian University residential court (see Fig. 4).

Further, to test the effect of the tree canopy cover on local urban temperatures, correlation analysis was performed between intra-urban temperature differences observed on hottest day of fieldwork (31 May 2021) and present tree canopy cover. Percent of the tree canopy was defined at three scales: 20-, 50- and 100-m radius surrounding each measurement site as shown in Fig. 6. Defined scales range from approximate size of a building to a size of a city block and are much finer than typically considered in UHI studies.

3.5. Microclimate simulations

3.5.1. Modelling approach

As previous studies acknowledged realistic performance of the micro-scale ENVI-met model in urban environment (Gatto et al., 2020; Maharoof et al., 2020; Taleghani et al., 2015), ENVI-met v.4.4.5 was used to investigate the cooling effectiveness of the Glasgow 'Avenues Programme' and alternative UGI treatments for the study area located in the city centre and delineated by the future 'Avenues' streets: Sauchiehall St., Holland St., Elmbank St. and St Vincent St. (Fig. 6). At the time of study, only the first of the case study streets (Sauchiehall Street) has been converted into an 'Avenue.' Building parameters required for the

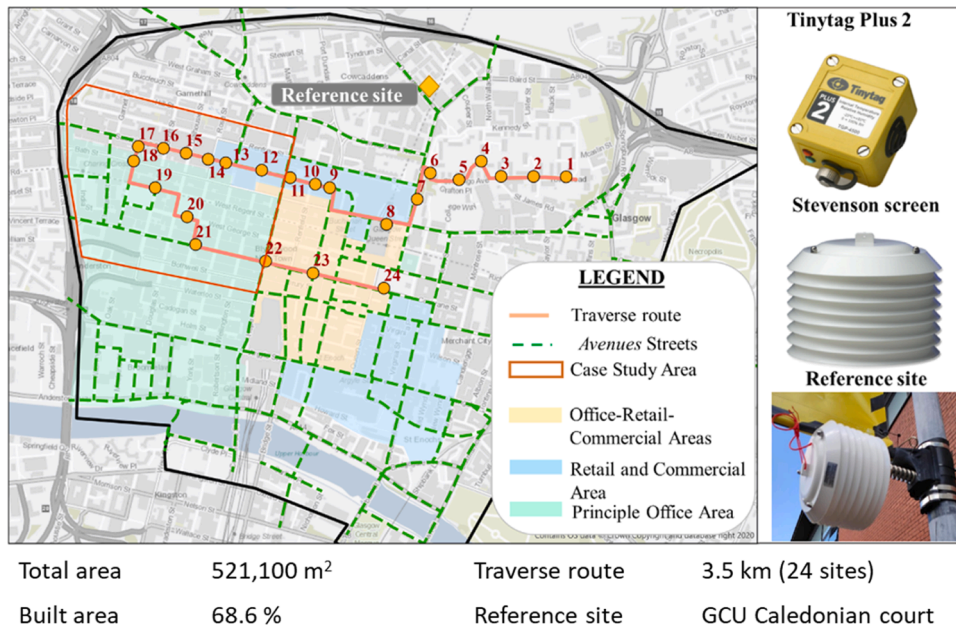


Fig. 4. Glasgow city centre study area, traverse route, location of reference site and equipment used.



Fig. 5. Street geometry within study area and temperature variations at sampling sites (31 May 2021).

simulation were obtained from OS Mastermap Topography Layer (Ordnance Survey, 2019) and LIDAR data (UBDC, 2021) as outlined in Table 1; surface properties, vegetation type and arrangement were defined through observational study and ‘Avenues Programme’ proposals. Meteorological data used for initiating the model was obtained from UK Met Office observations (Glasgow Bishopton, Location:

55.908622°N 4.5045200°W; Altitude: 59 m above mean sea level; Station type: Automatic) (Met Office, 2021). Fig. 7 illustrates model composition, work- and dataflow followed in this study.

Initially, model was calibrated and validated based on the fieldwork data obtained for 31 May 2021. Two iterations were performed to adjust input parameters and material properties, which allowed to acquire



Fig. 6. Buffer analysis and tree canopy cover within 20-, 50-100-m radii.

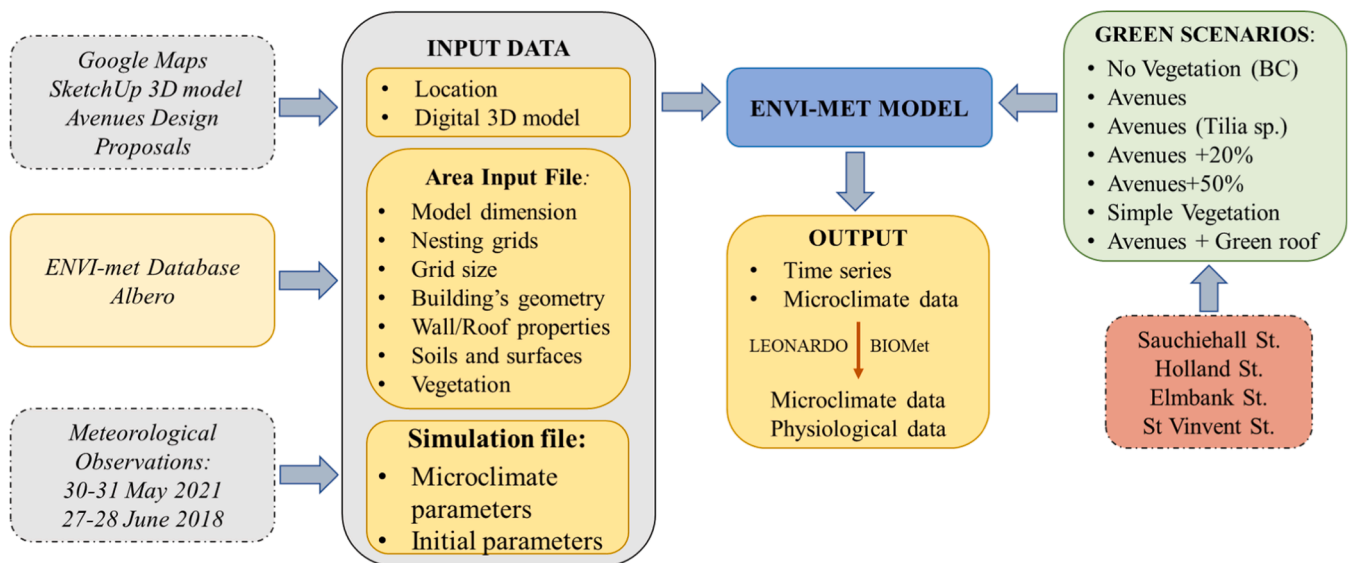


Fig. 7. ENVI-met model composition and workflow.

outputs statistically comparable to observations. Final model setting and parameters are shown in Table 4.

Further seven modelling scenarios with regard to different UGI types, tree number and species were simulated on 28 June 2018, the hottest day during the heatwave event of 2018. Table 5 provides explanation of the simulation scenarios. No vegetation scenario (Base Case), which reflects the current situation on investigated streets (except of Sauchiehall St.) was simulated for reference and comparison purpose. Trees number, selection of species and trees arrangement were defined based on observational study (Sauchiehall St.) and available design proposals for Holland St. and Elmbank St.⁶

Table 6 provides summary of the vegetation types used in the

simulations. As several studies showed that *Tilia sp.* trees have greater daytime cooling potential compared with other street trees (Gillner et al., 2015; Rahman et al., 2017), alternative trees scenario was investigated, which implied using *Tilia* trees in greening future ‘Avenues’ streets.

Design for St Vincent St. was not available at the time of this study, therefore assumptions about UGI arrangement and selection of species were applied based on the proposals for other streets.

Twelve receptors were introduced in the study area to enable comparison of simulations results as shown in Fig. 8 (please, refer to the Base Case – No Vegetation and Receptors image).

Table 4
ENVI-met settings and input parameters.

ENVI-met model input	Parameter	Model Settings
Model location	Glasgow	Coordinates 55.860916 N – 4.251433 W
Simulation settings	Date	28 June 2018
	Simulation start time	18:00
	Total simulation time	30 h
	Model dimensions	181 × 138 × 30 grids
	Size of grid cell	5 m × 5 m × 3 m
	Wind speed	2.2 m/s
	Wind direction	315°
	Roughness length	0.1
	Minimum temperature	10.7 °C
	Maximum temperature	29.2 °C
	Minimum relative humidity at 2 m height	33.9%
	Maximum relative humidity at 2 m height	98%
Timesteps	Solar angle for switching t0 to t1 (deg)	40
	Solar angle for switching t1 to t2 (deg)	50
	Timesteps	10–2 – 1
Surfaces & Materials	Soil type	Loamy soil
	Walls	Moderate insulation (default)
	Roofs:	Moderate insulation (default)
	Pavements:	
	- Sauchiehall Avenue	Granite, red coating
	- all other pavements	Dark pavement
Vegetation	Trees	Site specific trees: <i>Acer platanoides Deborah</i> , <i>Acer campestre William Caldwell</i> , <i>Ulmus Columella</i> , <i>Carpinus betulus Fastigiata</i> ,
	Shrubs	Hedge dense, height ≤ 2 m
	Grass	Average dense grass, 25 cm height

3.5.2. Analysis protocol

Given the focus on outdoor (pedestrian) thermal comfort, results were reported as air temperature (T_a), Mean Radiant Temperature (MRT) and Physiologically Equivalent Temperature (PET). MRT is a “uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure” (ASHRAE, 2001) and sums the human body exposure to all short- and long-wave radiation fluxes (direct, diffuse, reflected and emitted) in a given environment. As such, it is commonly used as a proxy for human comfort, especially in the outdoors (Johansson et al., 2014). The most accurate method to calculate MRT is to measure short- and long-wave radiation from six directions (up, down, left, right, front and back) and use Eq. 3 (Johansson et al., 2014):

$$T_{mrt} = \sqrt[4]{\frac{S_{str}}{\epsilon_p \sigma}} - 273.15 \tag{3}$$

where, S_{str} (Wm^{-2}) is the mean radiant flux density absorbed by the body, ϵ_p is the emissivity of the human body and σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} Wm^{-2}K^{-4}$).

According to Kirchoff’s law of thermal radiation, ϵ_p is equal to the absorption coefficient for long-wave radiation (standard value 0.97). The S_{str} is calculated according to Eq. 4:

$$S_{str} = \alpha_K \sum_{i=1}^6 K_i F_i + \epsilon_p \sum_{i=1}^6 L_i F_i \tag{4}$$

where, K and L are short-wave and long-wave radiation fluxes (Wm^{-2}) and $i = 1-6$ refers to the six directions mentioned above. F_i are the angular factors for the six directions and α_k is the absorption coefficient for short-wave radiation (standard value = 0.7).

More details on other procedures to derive MRT are given in (Johansson et al., 2014). In the present work, MRT were derived from the simulation software (ENVI-met).

PET, a thermal comfort index, was calculated in BioMet v.4.4.5 and further assessed in terms of thermal stress using a standardized scale (Matzarakis et al., 1999). PET range of 18 – 23 °C was considered as “no thermal stress” condition. This has been previously confirmed as valid for Glasgow (Kruger et al., 2013).

4. Results

4.1. LST profile, SUHI intensity and patterns

Citywide, mean LST varied between – 3.5°C to + 10.2°C and + 12.8°C to + 23.5°C for the cold (October to March) and warm (April to September) periods, respectively. Temperatures were the highest in June 2018, during a strong heatwave (Kendon et al., 2019). City centre warmed up to + 30.0 °C, while in other built-up regions LSTs ranged from 25.0°C to 27.0°C. Urban fringe areas were cooler with LSTs up to 25.0 °C.

The SUHI was most pronounced in summer (Fig. 9A), though some temperature discrepancies are observed in all seasons In Glasgow central areas, average summertime SUHI intensity ranged from 4.0°C to 6.0°C, with occasional 10.0°C peaks. Northern, eastern, and southern city corners, corresponding to parks, sports/leisure facilities and semi-natural areas were cooler. Four out of 23 Glasgow City electoral wards experienced SUHI intensities over 5.0°C: Dennistoun, Anderston/City/Yorkhill, Southside Central, Calton (Fig. 9B).

SUHI “hot” spots were identified based on the 3-year mean summertime intra-urban surface temperature variations retrieved from LANDSAT 8 OLI/TIRS as described in Sections 3.3.1–3.3.3. The threshold value of inter-urban SUHI across Glasgow City area was estimated at 22.9°C. Zones with surface temperatures exceeding the threshold were classified as SUHI “hot” spots. Spatial analysis showed that SUHI “hot” spots were localized in the City Centre area, and scattered to the north and south-west, corresponding to the residential and commercial areas, industry sites (to the west and along the river Clyde) and parking lots (Fig. 9B).

Previous studies indicate the presence of spatial autocorrelation for LSTs in urban areas (Dai et al., 2018; Kumari et al., 2019). Therefore, Global Moran’s I spatial autocorrelation index was used to determine the SUHI clusters in summer (mean of 2018–2020) and during the heatwave period (25 June 2018). The Global Moran’s I index values obtained for the summertime SUHI (2018–2020) and a heatwave day (25 June 2018) were greater than zero, which suggests that there is positive autocorrelation or highly clustered pattern. The obtained p-values were less than to 0.05 ($p \leq 0.05$) for both datasets, ruling out the basic assumption of randomness and independence in the data values. The obtained z-

Table 5
Summary of the ENVI-met simulation scenarios.

Scenarios	Short name	Description	Suggested UGI			
			Sauchiehall St.	Hollant St.	Elmbank St.	St Vincent St.
Base Case	BC	No vegetation	-	-	-	-
Avenues	AV	Tree species and number according to the <i>Avenues Programme</i> proposals	26 trees	14 trees	10 trees	28 trees
Alternative trees	AV_AT	Tree arrangement as AV but tree species changed to <i>Tilia sp.</i>	26 trees	14 trees	10 trees	28 trees
+ 20% trees	AV+ 20	20% more trees on the Avenues streets	32 trees	17 trees	12 trees	34 trees
50% trees	AV_50	50% more trees on the Avenues streets	39 trees	21 trees	15 trees	42 trees
Simple Vegetation	AV_SV	Grass and shrubs used for greening the <i>Avenues</i> streets	Same as in <i>Avenues</i> scenario	Grass and hedges, no trees	Grass and hedges, no trees	Grass and hedges, no trees
Green Roof	AV_GR	Trees species and arrangement as in AV scenario; green roof suggested for buildings with flat roofs (total area of $\approx 15,600$ sq m)	26 trees & green roofs according to area map	14 trees & green roofs according to area map	10 trees & green roofs according to area map	14 trees & green roofs according to area map

Table 6
UGI used in ENVI-met simulations.

ENVI-met Code	ENVI-met based tree species* *	Height/Width, m	Albedo	Use* **
A9	<i>Acer Campestre</i> *	12 / 9	0.18	S / AP
O7	<i>Acer platanoides</i> *	15 / 7	0.18	W / AP
B6	<i>Ulmus Culumella</i> *	10 / 5	0.18	S / W
B4	<i>Carpinus betulus</i> *	20 / 15	0.18	W
A1	<i>Tilia</i>	18 / 13	0.4	S / T / AP
H2	Hedge dense	≤ 2.0	0.2	
GB	Grass	0.25	0.2	
-	Green roof with grass	0.5	0.2	

* Tree species observed on the *Avenues* streets at the time of this study.

** Indicated tree species were selected from the ENVI-met trees database.

***Use: S - shade, W - windbreak, AP - air pollution filtering, T - temperature regulation.

score was greater than 2.58 (z -score > 2.58) for both datasets, therefore there is less than 1% probability that the observed pattern is an outcome of a stochastic process. Fig. 9C highlights the clustering of SUHI at data zone level. Red zones, “High-High Cluster”, indicate regions with high SUHI and located next to other heated areas, forming overheated clusters. “Low-Low Cluster”, given in blue, correspond to “cold” spots, mainly observed in green areas. Dashed red polygons demonstrate areas affected by heat stress during the heatwave. The red areas represented regions most effected by SUHI, indicating areas that are suitable for heat mitigation measures. Glasgow City Centre is among the most strongly affected areas.

4.2. Correlation between SUHI and UGI

Statistically significant ($p < 0.001$) Pearson correlation analysis at the data zone-level showed various degrees of relationships between SUHI and UGI types:

- total vegetation cover was strongly related, with SUHI ($r = -0.60$);
- trees demonstrated medium negative impact ($r = -0.43$) and slightly higher, when combined with grass ($r = -0.49$);
- grass and shrubs had negative weak impact on SUHI, with $r = -0.16$ and $r = -0.21$, respectively;
- shrubs combined with grass showed weak negative effect ($r = -0.36$).

GWR-based analysis revealed that depending on UGI types and location, the effects of vegetation on SUHI varied from (Fig. 9D):

- strong ($R^2 \geq 0.6$) to moderate ($0.5 \leq R^2 < 0.6$) in 75% of data zones; insignificant to moderate in 25% of data zones ($0.2 \leq R^2 < 0.5$).

These findings show that small, isolated patches of vegetation are not effective for cooling the clusters of overheated areas (except very local effects), and, therefore, complex greening strategies should be prioritized.

4.3. Mobile measurements and local-scale UGI effects

Air temperatures (T_a) varied along the traverse route. Mean within-route temperature range (i.e., difference between the coldest and hottest location) was 2.8°C in the afternoon and 1.9°C in the evening. Four days of fieldwork were warm (18.0°C), while on two others, temperatures were over 20°C . On the hottest day of field measurement (31 May 2021), the maximum and minimum temperatures were 28.2°C and 21.4°C , respectively, which is 10°C higher than the corresponding reference Glasgow daily mean maximum and minimum values (1981–2010) for May (Met Office, 2016). A cool island was observed in Townhead (sampling points: 1–7), due to the on-site vegetation, as local T_a were 0.2°C and 1.8°C lower than on reference site on warm and hot days, respectively. Sauchiehall St. was 0.79°C and 2.2°C warmer than the reference site on the warm and hot days, respectively. However, the highest temperature differences ranged from 2.9°C (Holland St.) to 4.6°C (St Vincent St.) and were recorded on streets without vegetation: Holland St., W Regent St. – Pitt St. and St Vincent St. (points: 18–23).

Along the traverse route, air temperature varied non-linearly with increasing tree canopy cover. Correlation was weak at the scale of 20 m buffer with $r = -0.42$ ($p < 0.05$), though the tree cover at the scales of 50–100 m had stronger effect at local temperature variations ($r \approx -0.5$, $p < 0.05$).

4.4. Heat mitigating potential of the Glasgow ‘Avenues Programme’ and alternative street greening schemes

With its final settings, ENVI-met model slightly underestimated ($\text{RMSE} = 2.40$, $R^2 = 0.88$) temperatures in the afternoon (at 15:00) and overestimated ($\text{RMSE} = 0.42$, $R^2 = 0.55$) for the evening hours (at 21:00), which correspond well with findings from previous studies (Tsoka et al., 2018).

Analysed scenarios showed air temperature mitigation effect of vegetation between 9:00 and 19:00, though trees slightly increased night-time temperatures, by trapping heat (Rahman et al., 2017). Fig. 10A highlights the T_a reductions observed for each greening scenario in comparison to Base Case (No Vegetation). The Avenues model demonstrated cooling capability with maximum T_a reduction of 0.91 K. Though, increasing tree cover by 20% (AV+20) and 50% (AV+50) had little additional effect on T_a : decrease of 0.92 K and 0.93 K, respectively. Alternative trees (AV_AT) scenario was the most effective (1.27 K reduction), demonstrating better cooling properties of the *Tilia sp.* trees. Simple vegetation (AV_SV) setting was less efficient and mitigated T_a by 0.88 K only, while Green Roofs (as specified in Section 2.5), in

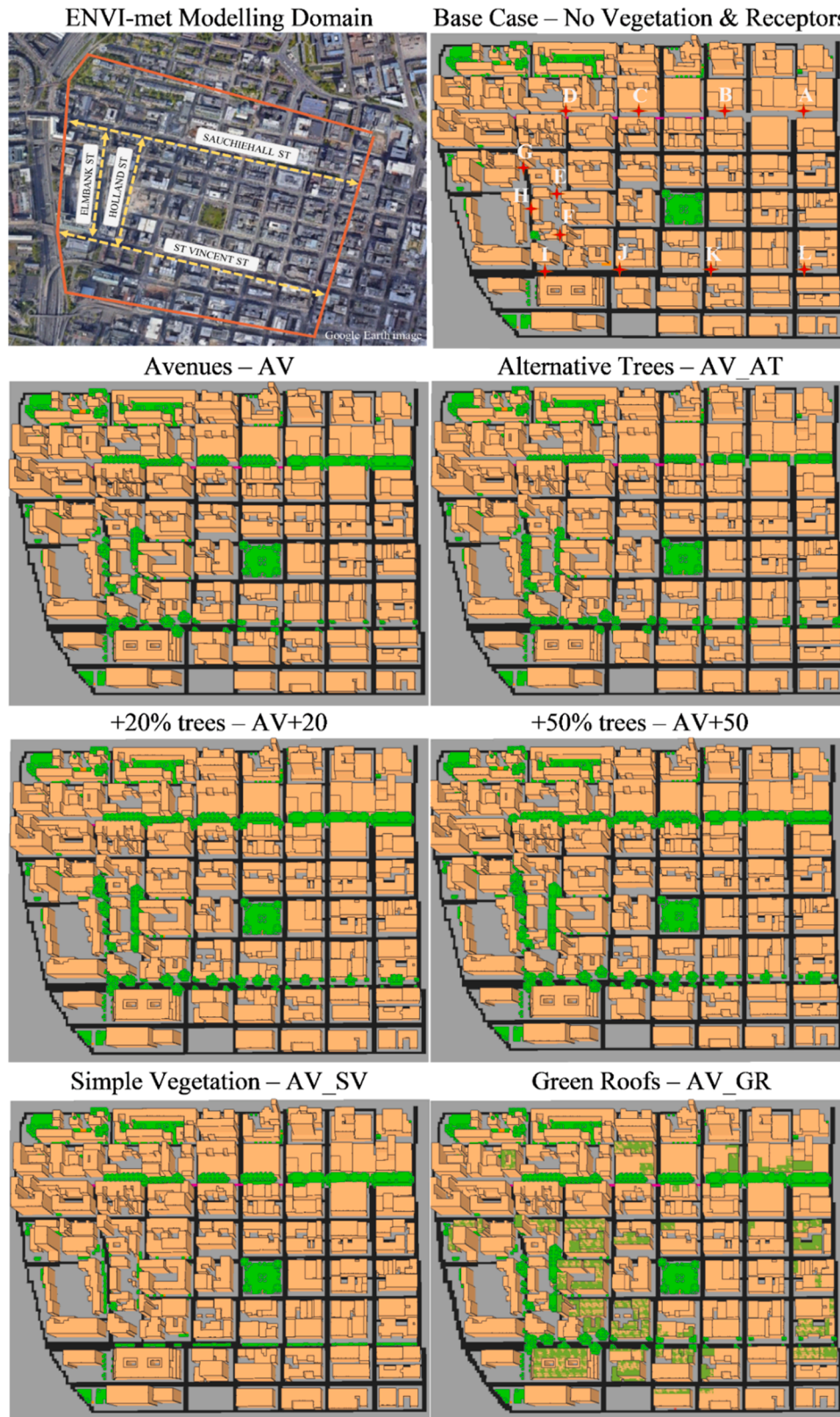


Fig. 8. Visualization of the modelling domain and seven simulation scenarios.

combination with trees as in the Avenues scenario, could cool the area by 0.96 K.

Effect of the greening on mean radiant temperature (MRT) was more pronounced, due to large reductions in surface temperatures within the street canyon. All tree-planting scenarios performed equally well and

reduced MRTs by 27.0 – 28.0°C on average, though Alternative Trees (AV_AT) model performed slightly better, with 29.0°C decrease. Green roofs (AV_GR) had little effect on pedestrian level MRTs with around 0.01°C MRT reduction, which was similar to findings from Portland, Oregon (Makido et al., 2019).

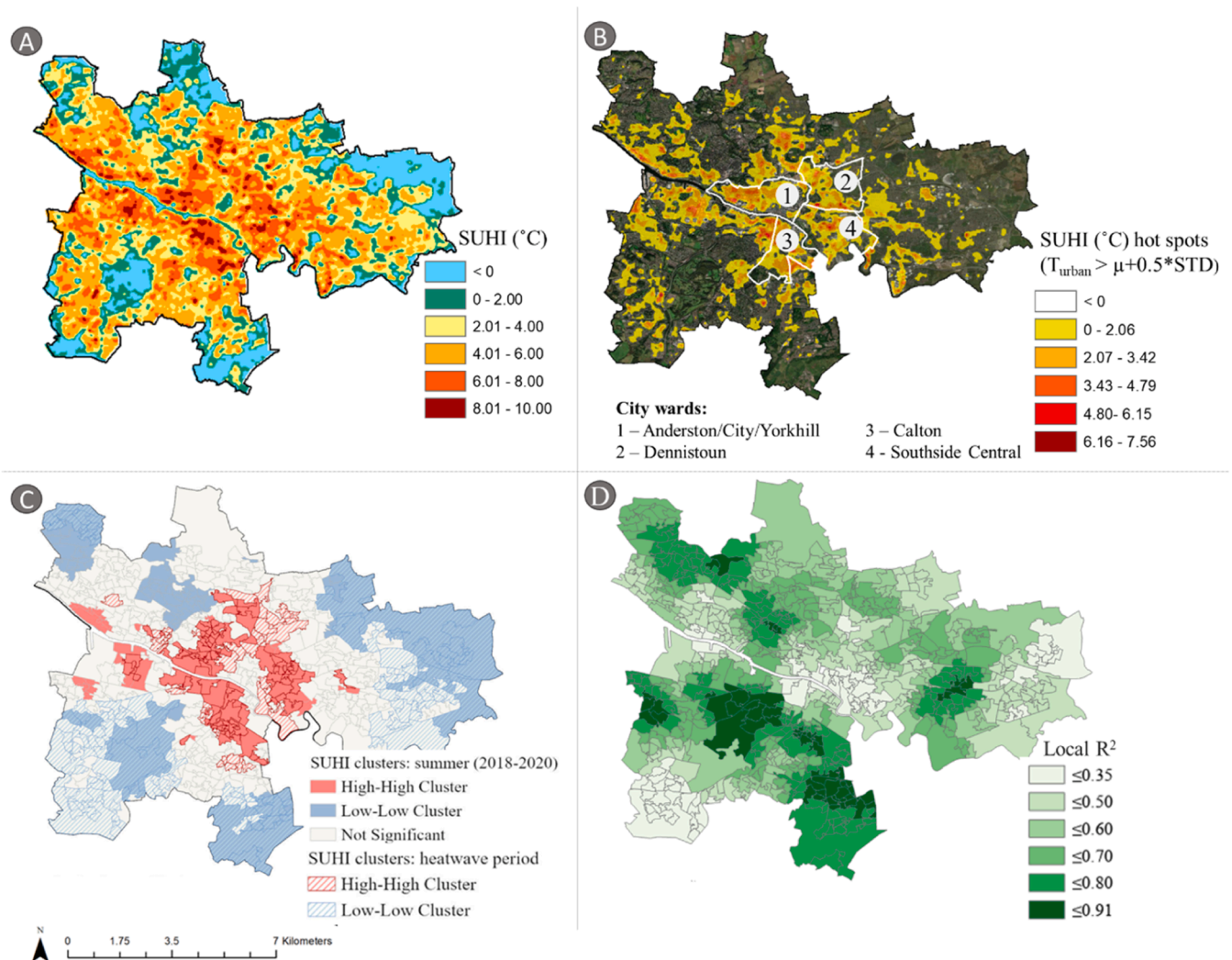


Fig. 9. (A) Mean summertime SUHI intensity in Glasgow; (B) SUHI "hot" spots; (C) SUHI clusters; (D) Local R^2 of GWR between UGI and SUHI; darker colour corresponds to areas of high goodness-of-fit.

PET, a thermal comfort index, was calculated at pedestrian level (1.5 m height) for 12 receptors located on Sauchiehall St., Holland St., Elmbank St. and St Vincent St (Fig. 8). Base Case (No Vegetation) scenario showed that, on a hot summer day, study area was thermally uncomfortable ($PET > 23.0^\circ\text{C}$) for 7–9 h, with PET peaks of $40.0 - 42.2^\circ\text{C}$ in the afternoon (12:00 – 16:00) (Fig. 10B). Trees demonstrated good potential to mitigate heat and pedestrian's thermal sensation from 'hot' thermos-physiological class observed in Base Case scenario to 'slightly warm' and 'warm,' as shown in Fig. 10B. In this graph, the coloured bars represent the range of observed PET values for each scenario, the line inside the "boxes" corresponds to the median. The lowest PET levels were achieved in the Alternative Trees model, PET value of 29.7°C , followed by the Avenues scenario, with PET equal to 29.0°C . In contrast, planting 20% (AV+20) and 50% (AV+50) more trees did not reduce PET further. However, increasing tree canopy could make more areas thermally comfortable by providing additional shading. Greening streets with grass and shrubs had a negligible effect on PET (mean reduction of 0.2°C). The impact of Green Roofs was also minimal, which implies that this strategy is not effective for the studied area.

5. Conclusions

As Glasgow City Centre Living Strategy intends to double population and encourages new developments in the central districts (Glasgow City

Council, 2019), the UHI consideration should be in focus of the area development process. This study has demonstrated that, in summer, urban areas of Glasgow are 4.0°C to 6.0°C warmer than the surrounding rural regions, though temperature discrepancies can reach up to 10.0°C in the regions with dense urban fabric. Intra-urban temperature differences observed within the city are of the same magnitude as urban-rural anomaly (up to 7.5°C) and play a key role in delineating urban "hot" spots, which due to imbalance in grey vs green infrastructure distribution, exhibit clustering pattern in data zones along the river Clyde in the central part of the city. These overheating clusters should be considered as strategic areas for UHI mitigation.

Findings demonstrated that vegetation is a key factor in lowering surface temperatures in 75% of Glasgow City data zones, with trees having most impact on LSTs, while shrubs show minor impact and grass – very little. Trees have more impact on urban heat at the larger scale, within 50–100 m radii (the size of a city block), while at finer scale (10–20 m) – the cooling is weak. Therefore, to counterbalance the clustering effect of SUHI, when planning an area, UGI (with priority to trees and grass) should also be incorporated in a clustered manner to disperse paved areas. Small and isolated patches of grass or trees are not effective at cooling the clusters of overheated areas, and only complex greening projects, e.g., the proposed Avenue trees cooling network or green management of parking, will yield effective temperature reductions.

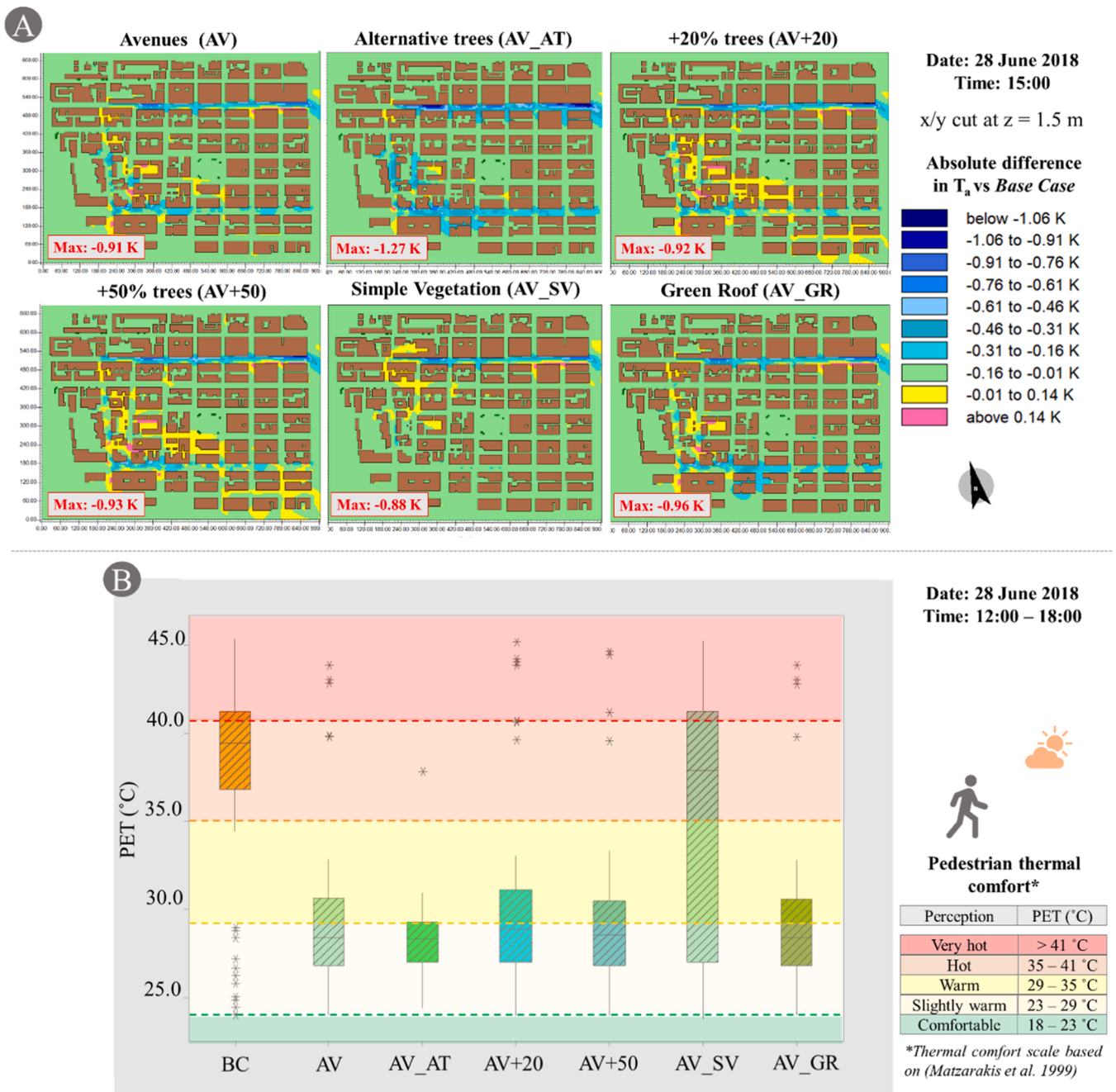


Fig. 10. Results of microclimate simulations: (A) Air temperature mitigation effect of each scenario in comparison to the Base Case; (B) Estimated PET values for all scenarios.

Microclimate simulations revealed that, at present state, Glasgow City Centre is thermally uncomfortable as, on a hot summer day, pedestrians experience strong to extreme heat stress ($PET \geq 40.0^\circ\text{C}$). Greening scheme proposed by the Glasgow ‘Avenues Programme’ for the Sauchiehall St., Holland St., Elmbank St. and St. Vincent St. can mitigate local air temperatures by 0.91 K and improve pedestrian thermal perception. Therefore, it can be assumed that the ‘Avenues Programme,’ when implemented at full scale, i.e., across 21 city centre streets, will positively contribute to the sustainability and urban climate resilience of the city and, additionally, will provide a successful case study of cooling potential of the city centre retrofitting project. The UHI mitigation effect of the ‘Avenues Programme,’ can be further enhanced by strategic placement of trees and revision of the selected tree species to prioritize the ones with better cooling properties. Thus, further economic

estimates of anticipated costs and benefits of each intervention might be useful.

Findings of this study contribute to existing knowledge on UHI in temperate climate and provide empirical evidence on the cooling potential of UGI types that can be further used to develop targeted, scale-specific cooling interventions as well as to inform and refine current guidance to achieve urban climate adaptation goals.

As this work has focused on daytime UHI only, further investigation of the diurnal UHI trends and thermal comfort effects on consecutive hot days might have useful implications for the heat-risk management. Other variables relevant to a street tree planting campaign, such as plant structures and physiology, irrigation levels, surface porosities on specific street canyons, etc. need to be explored to provide a wider understanding of the relationship between street trees and UHI mitigation in

Glasgow. The co-benefits/costs of the 'Avenues Programme' in terms of other ecosystem services/disservices (including air pollution) need to be explored.

Author statement

All authors jointly declare that the work presented here is entirely their own collective work, apart from instances where due acknowledgement is given via citation. Authors also declare that the manuscript is not under consideration for publication elsewhere.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rohinton Emmanuel reports financial support was provided by European Education and Culture Executive Agency. Rohinton Emmanuel reports a relationship with Glasgow Caledonian University that includes: employment.

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