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Article

Urban Green Systems for Improving Pedestrian Thermal Comfort and Walkability in Future Climate Scenarios in London

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Abstract: The purpose of this research is to investigate the thermal impact of urban green systems (UGS) (trees and living facades) and high albedo pavements on reducing the urban heat island (UHI) effect in London at the pedestrian street level. The research assesses the impact of UGS by suggesting practicable urban greenery-covering densities (25% and 50%) and using high albedo pavement in current and future climatic scenarios (2050 and 2080). This approach is intended to encourage pedestrians to walk longer distances for longer durations during the warmer months, following the Transport for London's (TfL) 2017 Healthy Streets initiative. The research seeks to measure the advantages and assess the possible impact on the comfort and activities within urban streets. The study adopts a quantitative research design using ENVI-met modelling and questionnaires. Simulation results, the subject of this paper, confirmed that, across three climatic scenarios, the optimal UGS for thermal comfort is 50% trees followed by 25% trees, dependent on street orientation and solar access. Living facades (LF) with 25% and 50% covering had no discernible effect on the comfort of pedestrians, whereas high albedo pavement increases heat stress.

Keywords: climate change; urban heat island (UHI); urban green systems (UGS); climate change mitigation; pedestrian thermal comfort

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1. Introduction

As a consequence of climate change, the frequency and severity of heat waves, as well as the continuous rise in air temperatures, have emerged as subjects of increasing public health concern [1–4]. Air temperature (Ta) increases, in conjunction with alterations in atmospheric circulation patterns and precipitation, have the potential to disrupt human health and wellbeing via diverse mechanisms. These include, but are not limited to, heat stress; increased occurrences of wildfires; the transmission of vector-borne and water-borne diseases; crop failure; and the consequential repercussions on food abundance and prices, economic welfare, population displacement, and potential conflict. There will undoubtedly be more deaths caused by excessive heat as temperatures rise [2,5]. In general, for every degree in Celsius above a location-specific threshold, the risk of death rises by between 0.2% and 5.5% [5]. Heat-related mortality in Europe may increase by 50 percent due to climate change, from an annual average of 152,000 to an annual average of 239,758 by 2080. In the UK, it is estimated that the number of heat-related deaths may reach over 11,000 annually by 2080. Heatwaves are also predicted to be more likely to occur in Western Europe and the UK [6].

Notably, the UK's urban areas are expected to increase by 118% [7]. However, it has been stated that the urban heat island (UHI) effect, in which heat is trapped and absorbed within urban canyons, worsens as urbanization continues in densely populated areas [8].

By the 2050s, summer temperatures in the south-east of the UK are projected to increase by 3.5 °C, and by the 2080s, they are projected to increase by 5 °C. It is also predicted that the frequency with which central London experiences temperatures that are 9 °C higher than the surrounding greenbelt will rise [9]. This is due to the UHI, which may raise summer evening temperatures by 5 to 6 °C [10]. The reduced solar heat gain via leaf shade [11]; increased solar reflectance from leaf shadings' high albedo [12]; and enhanced latent cooling from evaporation and transpiration all contribute to reducing the UHI [13].

The dense layout of urban areas, dominated by impermeable surfaces; for instance, roads, buildings, and parking lots, trap more heat than the sparser configuration of peri-urban and rural areas, which are dominated by more open spaces [14]. In order to mitigate climate change and reduce the UHI effect, Urban Green Systems (UGS) including green walls, green roofs, high albedo surfaces, trees, and living facades (LF), may enhance the microclimate of the built environment, especially in dense urban areas. UGS has the potential to ameliorate urban areas through bolstering the green cover, thus enhancing air quality, precipitation attenuation, and reducing outdoor and indoor air temperatures [8,10]. Importantly, UGS mitigates the UHI effect and provides a climatic shelter for pedestrians to enjoy walking during warmer seasons. As a result of its cooling effect, shading capacity, and reduced heat vulnerability of the surrounding areas, it exerts a considerable influence on the local microclimate [15–18]. UGS might be implemented in a variety of ways, including trees over roadsides and city walks, residential gardens, green and living facades, and green roofs [12,19,20]. These green coverings may be created at varying geographical scales with varying levels of integration [21,22] to improve the microclimate [23–25] factors (including relative humidity, air temperature, and wind speed [24,25]. UGS are also known to have a considerable beneficial influence on life-cycle energy and carbon savings, humidity, noise levels, and air quality at a localized level [26–29]. As a result of boosting biodiversity, they may also have substantial positive effects on a city as a whole [30,31]. In addition to its ability to mitigate the effects of climate change and pollution, UGS also enhance social cohesion, mental health, and wellbeing [24,32,33].

With the primary goal for a healthy environment and climate change mitigation, The Adaptation and Resilience in a Changing Climate (ARCC) research network in the UK has explored the creation of adaptation analysis tools and programs for urban areas, concentrating on the built environment, transportation systems, and infrastructure [34]. The programs are designed to improve urban vegetation cover as an effective approach to mitigate the impact of predicted climate change in urban areas [11]. This approach is also referred to as a passive climate change adaptation strategy as opposed to active adaptation strategies, which are energy intensive and unsustainable. Passive adaptation strategies decrease energy consumption, which in turn reduces greenhouse gas (GHG) emissions [35] and air pollution [36].

Green walls have been found to have a tangible impact within an urban canyon. However, green roofs have a greater impact on the roof level surface temperature [24]. The Institute of Physics in Berlin conducted a study using 56 planter boxes spread over four floors, which found that a mean cooling value of 157 kWh/day could be achieved due to the evapotranspiration of UGS [33]. The maximum surface temperature may be lowered by 2.5 °C if green cover is increased by 10%, according to another study [37] on the potential impact of green infrastructure on cities' adaptation to climate change by 2080. In contrast, removing the same percentage of green cover would lead to a 7 °C increase in surface temperature [38]. In temperate climates such as London, a combination of green roofs and green walls led to the optimal reduction in urban temperatures. Concerning green walls, the temperature benefits realized ranged between 1.7–2.1 °C and a maximum of 2.6–3.2 °C, whereas they varied from 3.0–3.8 °C and a maximum of 3.6–4.5 °C for green roofs and green walls [39].

How people react to the surrounding climate variables around them is mainly influenced by how comfortable they feel in those surroundings. Human thermal comfort is influenced by both external climate parameters (air humidity, mean radiant temperature, air temperature, and wind speed) and individual variables (type of activity, metabolic rate, and clothing level) [40]. According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Pedestrian Thermal Comfort (PTC) is "the state of mind that expresses satisfaction within the thermal environment", while it has been noted that PTC is "a psychological approach to investigate thermal comfort" [41]. Humans' psychological parameters and expectations towards their surroundings were the basis for the identification of PTC [42]. The term PTC is subjective and dependent on people's behavioral and responsive activities in accordance with the context they are in due to the wide variation, broad explanations, and understandings of what satisfies humans. This concept of thermal satisfaction may even vary across individuals from the same geographical and climatic region.

Notably, Urban Green Systems inclusive of vertical green systems and green roofs, in addition to trees, have not been sufficiently studied regarding benefits and environmental impact in future climate scenarios, particularly in temperate climates. Thus, the present study focuses on determining the UHI effect and mitigation through UGS in current and future (2050s and 2080s) climate scenarios. The study investigates the importance of evaluating the impact of Urban Green Systems (UGS) on reducing the Urban Heat Island (UHI) effect, as it is acknowledged as one of the most effective strategies for mitigating climate change.

2. Research Methodology

The study adopts a quantitative research methodology aiming to investigate how UGS influence pedestrians' comfort. This is achieved by ENVI-met software v4.4.3 Beta V simulations, field measurements to validate the results (subject of this paper), followed by a questionnaire survey to understand how people perceive the established UGS strategies. First, the modelling and simulation of the base case of a typical central London canyon with no vegetation (0%) is undertaken, before applying UGS with a 25% and 50% living facade and tree alternatives in addition to applying high albedo materials to all pavements (which represent 66% of the canyon area). The simulations are undertaken for 2018, 2050 and 2080 climate scenarios during the summer months in order to measure their influence on the pedestrian thermal comfort. The ENVI-met simulation results determine that the outdoor thermal comfort is measured based on Physiological Equivalent Temperature (PET) as a reference to evaluate alternative solutions that improve the outdoor comfort level. PET was developed specifically for outdoor environments as an index that considers all basic thermal processes based on the thermo-physiological heat balance model. PET is grounded on a predictive model of human energy balance that calculates skin temperature, the sweat rate, the body core temperature, and, as an auxiliary variable, the clothing temperature [43,44]. Concurrently, site measurements were recorded to validate ENVI-met simulation results.

2.1. Case Study: Oxford Street, London, UK

London is considered one of the cities with the highest nitrogen dioxide pollution concentration in the world at 32.3 micrograms per cubic metre of air ($\mu g/m^3$), with Oxford Street being one of the top polluted streets (83.9 $\mu g/m^3$) across the UK for all pollutants [45,46]. Oxford Street is one of the major streets in West London with a length of 1.2 miles, with the majority of its buildings being used as retail shops and department stores. It runs from Marble Arch to Tottenham Court via Oxford Circus and is normally visited by half a million visitors daily, making it Europe's busiest shopping street. Pedestrians tend to walk more on London's main streets, including Oxford Street, leading to several walking congestions happening across different times of the day. For instance, the highest period for tourists is late afternoon, while for the locals it is late morning. Usually, the peak flow is during lunchtime and the evening rush hours. Women tend to walk more than men and non-tourists more than tourists within the central London area [47]. The Oxford Street canyon between Orchard Street and Park Street is characterized by an average Height: Width of 1:1 (30 m), while the length of the building semi-square block is 120 m for each side and the street canyon length is 120 m. Several studies have asserted that similar canyon dimensions need to be investigated for the purpose of improving pedestrians' thermal comfort (PTC), especially during the summer season [48,49]. Thus, measurements are taken within the North-South (NS) street (S1) canyon and the East-West (EW) street (EW) canyon, which represents Oxford Street. The canyon buildings are determined and classified based on their height (low, medium and high-rise). Since UHI is mainly clearer when the height of the buildings is between 1 and 3 times the width of the selected Oxford Street canyon, it is mainly based on 1:1 canyon geometry; Figure 1.

Figure 1. Oxford Street width and building use and heights, indicating the 1:1 canyon geometry (Authors, 2020).

2.2. ENVI-Met Software

ENVI-met has been determined as one of the only tools that support the research objective of microclimate modelling. The software was developed in Ruhr-University Bochum in Germany by the Climatology Research Group for modelling surface-plant–air interactions in the urban environment [50]. It is specifically intended to investigate the changes to the landscape and the built environment in urban areas. With around 3000 independent studies, ENVI-met is the most assessed microclimate modelling tool, demonstrating its abilities and broad options to precisely simulate the outdoor microclimate. It allows for the analysis of design effects on the local environment, the condition of the ground plane, building materials, and the use of vegetation on walls, roofs or both to help address urban heat stress. ENVI-met allows different climatic factors and their influence and reflections on the built environment to be simulated, whether outdoors, indoors, shaded or exposed to the sky environment, including all liveable factors such as trees, vegetation, water features, etc. [51–53]. One of the core benefits of ENVI-met software is that it handles multilayer vegetation in detail such as soil conditions (e.g., moisture), type of vegetation cover, etc., and develops site-specific vegetation profiles. It also applies thermodynamic processes and computational fluid dynamics (CFD) in its analyses.

One of the ENVI-met limitations is that the wind speed and cloud cover are kept constant at the model boundary conditions during the simulation period. Modelling scenarios are based on case-study canyon areas selected for their mix of building types and UGS characteristics. The ENVI-met software version used in this study is v4.4.3 Beta V. A three-dimensional model is developed to predict the influences on the microclimate within the case study based on an energy balance model. It takes into consideration the physical processes between vegetation, building, atmosphere, and ground and simulates them within an urban area with a high temporal and spatial resolution, which enables a detailed study of microclimatic variations [40].

These simulations are undertaken during the summer season (21 June–21 September) for three climate scenarios, current climate, 2050 and 2080. Simulations for 2050 and 2080 are undertaken using the UKCP09 high emission scenario. High emissions scenario files (A1F1) were selected for simulations due to their probability of occurrence exceeding 90%, signifying a high likelihood that future weather data will not fall below the predicted values by 90%. Conversely, medium emissions (A1B1) possess a 50% occurrence probability, indicating that half of the predicted weather data will not be less than the actual future weather. A comparative analysis was conducted between the Met Office's 2018 weather files for Kew Gardens, London, and Exeter University's weather files for Islington, London, under the UKCP09 model. Variances were observed in Wind Speed (Ws) and Global Solar Radiation (GSR) patterns [54–56].

The UKCP09 [57] classified the climate of the twenty-first century into three possible scenarios, taking into consideration the uncertain response of regional climates and the natural variability due to global warming. These scenarios are short "next one decade" 2020s, medium "mid-century" 2050s, and long-term scenarios "by the end of the century" 2080s. Potential risks for the UK under the medium emissions scenario [54,58] indicate the climate change science affirmations, considering that 30 years is the average change period; thus, it could be sufficient in providing estimated annual and seasonal climate variables. Thus, it is commonly used predominantly by the UKCP09 with 1961–1990 as the time base case. Based on these inputs, UKCP09 provided seven overlapping periods of climate change between 2010–2039 to 2070–2099. On the other hand, the Climate Change Risk Assessment (CCRA) has been focusing on a non-overlapped 30-year-period, covering the years between 2010 and 2099. Both systems have been using the central decades of the 30-year-period, which are the 2020s, the 2050s, and the 2080s.

There have been three steps undertaken in running ENVI-met simulations. First, we adjust the model geometry through the Spaces File ENVI-met software tool, which includes the built environment including urban canyons. Following this, simulation folders are created for the required simulation in addition to any further meteorological details regarding the climate inputs (temperature, wind speed, relative humidity, etc.). Finally, the simulations are run through the Leonardo application, which analyses and visualizes results and simulation outputs in graphs and 2D and 3D maps. Following running the simulations of the different UGS alternatives for the current climate, a comparison was undertaken between simulation results and on-site measurements within the canyons in order to calibrate and validate the ENVI-met tool.

To avoid weather change throughout the summer, the researchers proposed to use the mean hourly data across the whole summer season. In comparison, some other studies used the mean data for the hottest week [59], or the hottest three days [60,61], or the hottest one day [62,63] which may indicate biased methodologies to illustrate an extreme difference before and after placing alternative solutions. However, because the ENVI-met simulation was run for the whole 24 h, the measurements of UGS influence were considered for the warmest hour of this (24 h) at 16:00, in order to determine the influence of applying different UGS with the determined variation of percentages on thermal comfort.

The simulation running time is set by the user with a typical running time of one day (24 h), which reflects the average 24 h of a full summer season. Simulating and generating data for each hour consumed approximately two hours due to numerous outputs and extensive calculations. This has led to two days (48 h) of running simulations for each 24 h climatic scenario. This estimation was calculated based on the researchers' trial simulation for 0% green areas and during one day of the year: 23 June 2018. The number of simulations would be for three years (2018, 2050, and 2080) for three vegetation scenarios (0%, 25%, and 50%) and for three different UGS types which are trees, green walls, and high albedo for pavements.

2.3. Field Measurements for ENVI-Met Model Validation

Ensuring the accuracy of microclimate simulations is imperative for robust scientific investigations. In this study, we utilized ENVI-met software for urban microclimate modelling; to validate its performance, a comprehensive set of field measurements was conducted. In order to validate the ENVI-met software data concerning the mean radiant temperature (Tmrt), ground surface temperature (Ts) and building wall temperature (Tw); the researchers developed a schedule to capture real time data using handheld equipment on site. The recording of Tmrt, Ts, and Tw have been undertaken using the handheld instruments during a typical summer week (17 and 26 July 2019). Onsite measurements were captured each day between 10 a.m. and 6 p.m. Hourly data of of Ta, Tmrt, and RH were measured and recorded using WBGT8758 Heat Index Monitor (General Hardware Manufacturing Co., New York City, United States Surface), surface temperature using TiS55-Thermal-Imager (MyFlukeStore, Wilmington, California, United States), and wind speed using Testo-425 (Testo Ltd., Alton, Hampshire, United Kingdom). These data serve as the simulation input values for the ENVI-met model. Subsequently, both recorded measurements using the weather station and the handheld equipment across the study duration were analyzed to calibrate and validate the ENVI-met model data input accuracy.

This research contributes to the ongoing discourse on microclimate simulations in urban environments. The accuracy and reliability of ENVI-met in predicting microclimatic variables have been affirmed through the meticulous validation against field measurements. This aligns with the recommendations and challenges outlined by [64,65] in their recent guidelines and reviews on the urban microclimate simulation accuracy. The study builds upon earlier works [51–53], reinforcing ENVI-met as a reliable tool for thermal analysis and microclimate prediction. Our approach, grounded in both field measurements and simulation, enhances the scientific rigor of microclimate studies, particularly in the context of sustainable urban development and the mitigation of UHI effects.

3. Results

3.1. Exploring the Effectiveness of UGS Alternatives in Different Climatic Scenarios

In order to evaluate the effectiveness of the proposed UHI mitigation scenarios in relation to the Physiological Equivalent Temperature (PET), the empirical model will be testing the base case with the actual street asphalt (albedo = 0.02) and unclean concrete sidewalks (albedo = 0.04) with 0% UGS within the canyon. Two different green systems—trees and living facades—are then applied at a 25% and 50% density. The high pavement albedo (HPA) in the form of white concrete (Albedo = 0.8), is also tested at 66.6%, which represents all pavement areas. It must be noted that the vegetation in central London is nearly zero in the main streets, as with the case study canyons, hence setting the base case at 0% vegetation.

The simulations are then undertaken for the four different scenarios, as shown in Figure 2—base case, trees, living façade, and pavement albedo, using 2018 Met Office climatic data in order to evaluate their influence on UHI mitigation by using 12 receptors (R). Receptors are selected points within the model horizontal plane, where processes in the soil and the atmosphere are captured in detail to show all environmental interactions which influence the human thermal comfort such as Ta, Ws, Tmrt, etc. The two different ratios for each vegetation type are then applied by remodeling the current case from 0% to 25% and 50%. As the Greater London Authority (GLA) plans to increase the green areas in London between 38.4% and 50%, the researchers determine 50% as the maximum level of vegetation in the study [66,67].

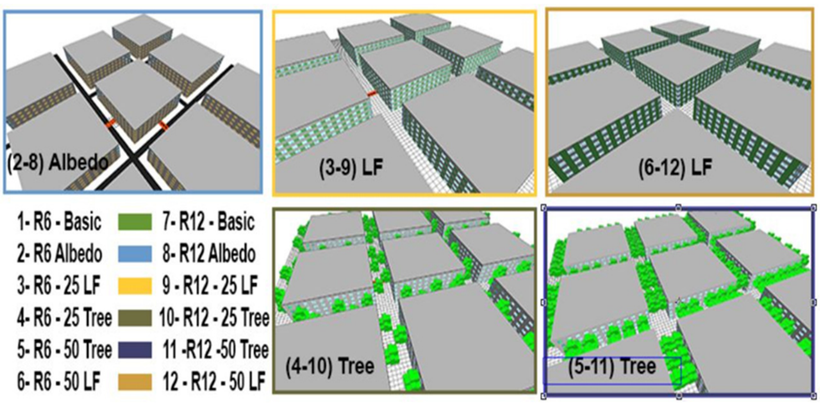
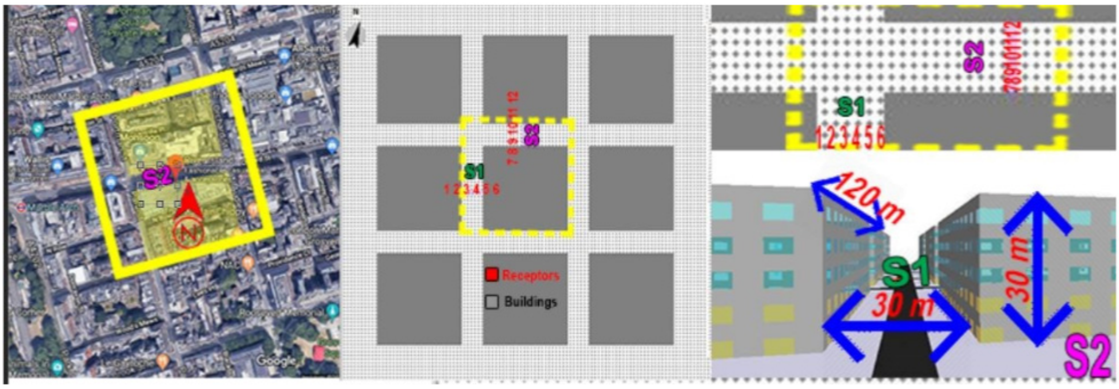


Figure 2. UGS alternatives: 25% and 50% LF, 25% and 50% trees, and high albedo pavement.

Different canyon orientations in London require different UGS percentages; therefore, the suggested study area, as in Figure 2, models the canyons identified on and around Oxford Street, central London. This study area is divided into perpendicular streets. North-South (NS) street represents Regent Street as the NS canyon, while Oxford Street represents East-West (EW) street and is perpendicular to Regent Street. Using ENVI-met software, the canyon geometry is built using detailed building specifications, dimensions, and materials (Table 1). Receptors (R), are located in the middle of the canyons at which calculations are recorded in the simulations. R6 is located in NS street and R12 in EW street. This is then followed by proposing five different alternatives measured across 12 receptors; six receptors in each street orientation. The five proposed UGS alternatives are: high albedo pavement, 25% Living Façade, 50% Living Façade, 25% trees, and 50% trees. UGS alternatives are illustrated in Figure 2, cool pavement (high albedo pavement); for NS [2-R6 Albedo] and EW [8-R12 Albedo]; 25% LF for NS [3-R6-25% LF] and EW [9-R12 25% LF]; and similarly with the tree alternatives, as per the ENVI-met simulation results in Figure 2.

Table 1. ENVI-Met model parameters and settings.

ENVI-Met Model Area Specification



Main Model Area	520 m × 520 m × 63 m
Number of Grids in X, Y, Z	104 × 104 × 21
Grid Size in metres Dx = size of X grid Dy = size of Y grid Dz = size of Z grid	104 × 104 × 21 Dx = 5 Dy = 5 Dz = 3
Each Canyon Dimensions (Length × Width × Height)	120 m × 30 m × 30 m

ENVI-Met Model Tsurface Map of Base Case Climate Scenario

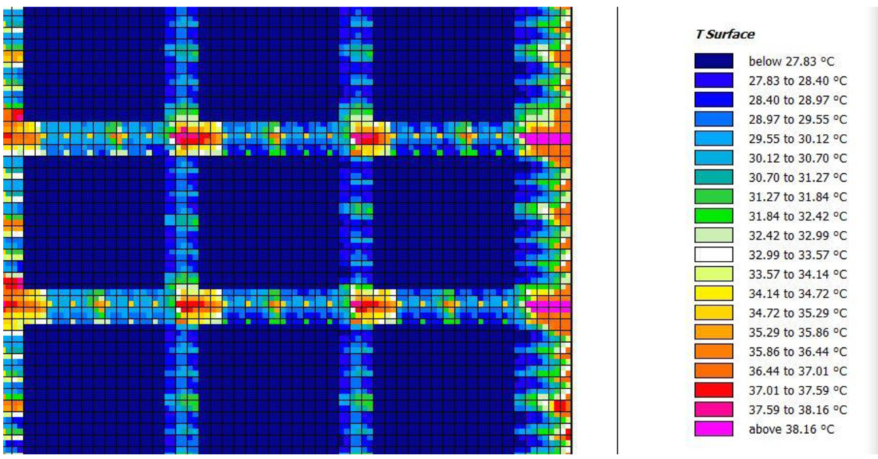


Table 1. *Cont.*

Urban Construction Material	
Building material	Wall: Default wall—Moderate insulation (Concrete, insulation, and plaster)—31 cm width Windows: Heat Protection glass—Thickness 3 cm—Absorption 0.05—Transmission 0.9—Refection 0.05—Emissivity 0.9—Thermal conductivity 1 Roof: Roofing Tiles—(Concrete, insulation, and plaster)—30 cm
Soil	Road: asphalt-Albedo 0.4, Emissivity 0.9 Pavement: Dirty paved concrete: grey—Albedo 0.04, Emissivity 0.9
Receptors (R)	
S1 (North–South) Street Canyon	1, 2, 3, 4, 5, 6
S2 (East–West) Street Canyon	7, 8, 9, 10, 11, 12
Location	
Oxford Street, Westminster, London, UK	Latitude (deg, +N, −S) = 51.51 Longitude (deg, −W, +E) = −0.16
Model Rotation from Grid North	−15.4
Start and duration of the model	
Date of simulation	Average of whole summer season on an hourly basis
Start time	6:00 a.m.
Total simulation time (hours)	24
Urban Green Systems	
Tree	London Plane tree—Height 20 m—Diameter 15 m—Albedo 0.18
Living Façade	IVY (Hedra Helix)-Deciduous—Albedo 0.2—LAI 1.5
Cool Pavement	Light concrete pavement—Albedo 0.8
Initial Meteorological Conditions (Simple Forcing)	
Roughness length at the measurement site Wind Direction (degree)	0.010 225
The initial temperature of the atmosphere (C)	
Simple forcing: Air temperature (C)	Min 13.9 at 05:00 h; Max 23.9 at 16:00 h
Simple forcing: Relative humidity (%)	Min 47.4, at 16:00 h; Max 89.3, at 06:00 h
Background Pollutants	
CO_2	410
Biometeorological Factors	
Clothing (clo)	0.30
Metabolic work (W)	80
Walking speed (m/s)	1.21

Within the Spaces File, different types of vegetation can be integrated, whether they are trees or living façade; the vegetation properties and details are found and edited in a separate window (Albero), where all vegetation species (London/Hybrid Plant with the actual name Platanus × Acerifolia), specifications (height—20 m and diameter—15 m), and details (deciduous tree; foliage shortwave albedo—0.18; and foliage shortwave transmittance—0.30 with a leaf weight of 100 g/m^2 and an isoprene capacity of 12, in addition to a root depth of 1.5 m; diameter of roots is 10 m) are applied. the total number of trees for the street canyon (120 m × 30 m = 3600 m^2) with 25% tree coverage are (5 trees × area of each tree (3.14 square radius) = 5 × 22/7 × $(7.5)^2$ = 883.1 m^2, while for the street canyon with 50% tree coverage it is 10 trees × area of each tree (3.14 square radius) = 10 × 22/7 × $(7.5)^2$ = 1766.2 m^2.

An ENVI-met simulation was then undertaken for the future climatic scenarios in 2050 and 2080, in order to detect the impact of the changing climate on pedestrians within both street orientations. Consequently, results were extracted from ENVI-met in the form of graphical illustrations and Excel files representing the data calculated by the Receptors within both canyons. An in-depth analysis is undertaken in order to explore the influence of each individual UGS alternative in the three climate scenarios to assess the most appropriate UGS alternative for each canyon orientation in each scenario. These results were further analyzed, compared, and discussed according to each PTC (Ws, RH, Ts, Ta, Tmrt, PET, PMV, and PPD). As illustrated in Figure 3, the change in wind speed (Ws) increases in EW to range between 90% and 140%, while for NS the Ws change ranges between 60% and 80%. Across all climate scenarios, placing more trees within canyons with higher Ws leads to a reduction in Ws, as expected.

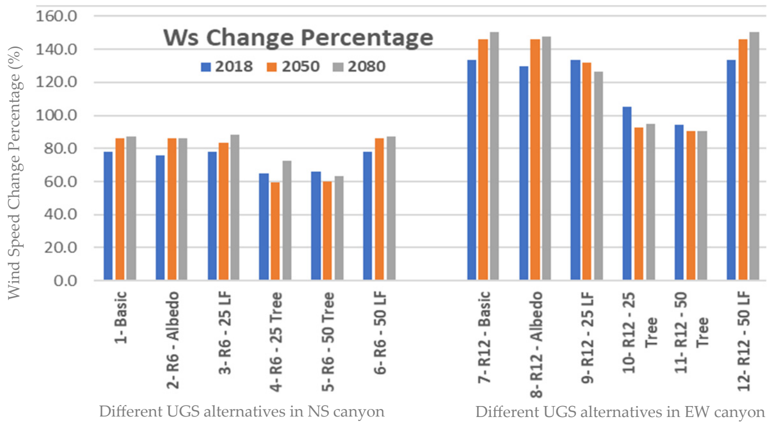


Figure 3. Wind speed change percentage across different years: 2018, the 2050s, and the 2080s.

Relative humidity (RH) is constant across different canyons as indicated in Figure 4. However, it should be noted that 2018 had the highest RH, with 50% then declined by 2% in the 2050s and further declined by 8.8% in the 2080s, which indicates that summer seasons will become drier and hotter in the near future. Trees and LFs are the best alternatives for low RH, as they increase RH to compensate for the dry weather. Both LF percentages and trees with 25% had a similar RH percentage of increase while trees with 50% coverage had the highest RH across all climate scenarios with an increase of between 6% and 10% in RH compared to its base case in each climate scenario. Notably, the drier the climate becomes, the higher the increase in RH provided by trees or LF becomes. The increase in RH, especially with a high percentage of UGS 50% trees or 50% LF, may be due to evapotranspiration leading to increased RH in the air particularly within future climates in the 2050s and 2080s; this will help moderate the climate in summer as it becomes drier. Therefore, placing more trees in the canyon in future climatic scenarios is not only helpful for reducing the Ta, but also to increase RH and hence improve the overall thermal comfort levels.

PET was developed specifically for outdoor environments as a thermal comfort index that considers all basic thermal processes based on the thermo-physiological heat balance model. PET is one of the suggested indices in new German guidelines and is used to predict changes in the thermal component of urban or regional climates for urban and regional planners [44]. PET is grounded on a predictive model of human energy balance which calculates skin temperature, sweat rate, body core temperature, and, as an auxiliary variable, clothing temperature [68].

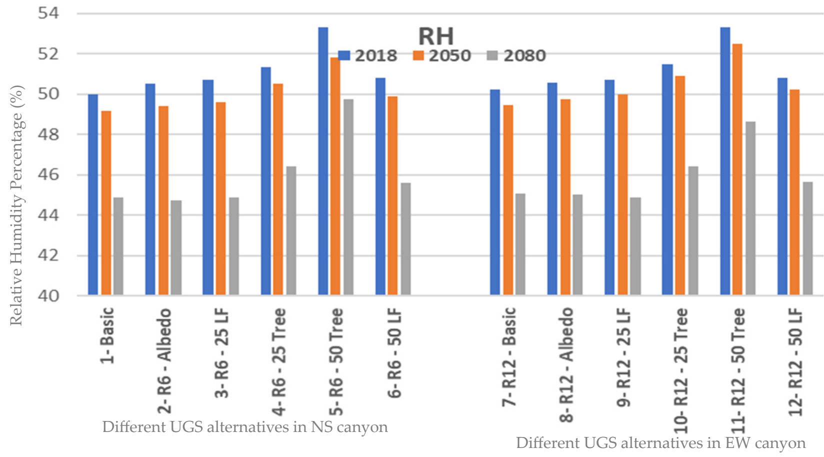


Figure 4. Relative humidity in 2018, 2050, and 2080.

Figure 5 indicates that with future climate scenarios, PET increases at variable levels across both street canyon orientations. PET has increased in both NS and EW canyons, by 2.5 °C and 7.5 °C in 2050 and 2080, respectively. However, the air temperature increase is the same; the temperature in the EW canyon was 5 °C higher than for the NS canyon. This may indicate that the amount of global solar radiation (GSR) received by the EW canyon is higher than the amount received in the NS canyon. Since PET is the main factor to judge PTC in each year as it takes into consideration all thermal comfort factors (Ta, Tmrt, Ws, and RH), it is very important to compare PET in order to determine PTC in each climate scenario, as shown in Figure 5. The EW was higher in Ta and PET across all climate scenarios due to the exposure to longer hours of direct GSR, as the canyon has an EW orientation. PET in the EW canyon was higher than NS by 5.4 °C on average, which represents 23.7%, 21.2%, and 20% for 2018, 2050, and 2080, respectively. Even though the temperature difference between EW and NS decreases with time, it is worth mentioning that the average Ta is increasing with time which confirms that using UGS becomes an essential solution to mitigate impacts of climate change.

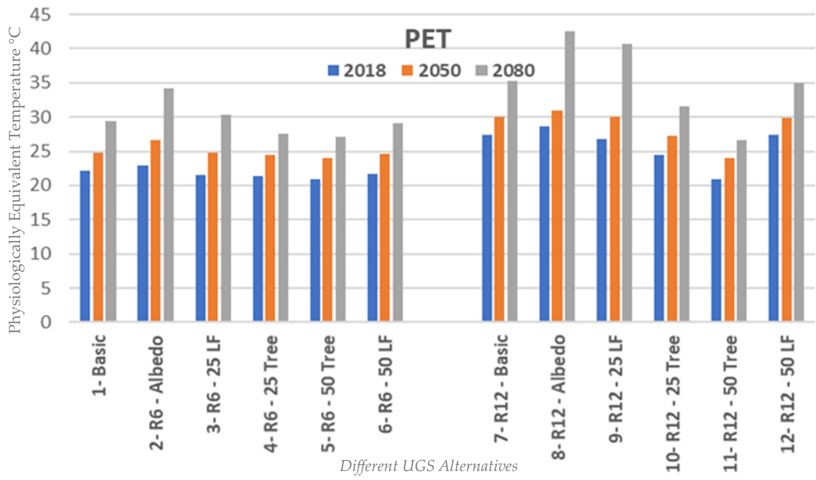


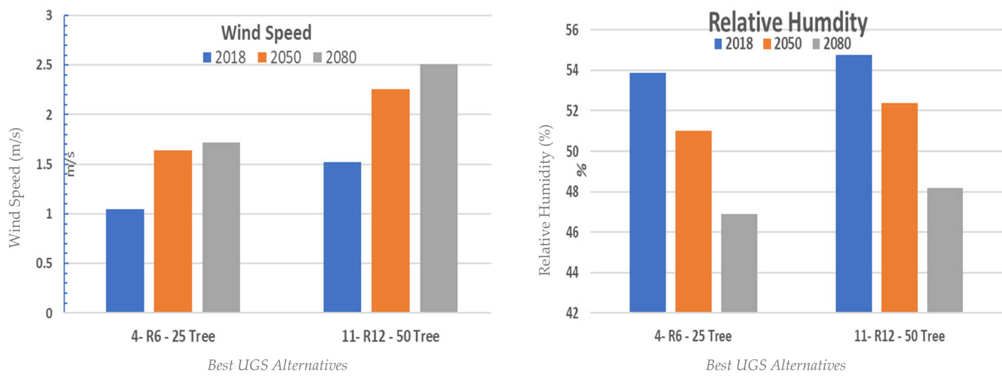
Figure 5. PET in NS and EW canyons for different climate scenarios in 2018, 2050, and 2080.

It is also worth mentioning that, within EW, 50% of trees is the best alternative for UGS across all climate scenarios, while NS shows that across different climate scenarios alternatives could be different depending on the level of climate change adaptation. For instance, in 2018 in NS, trees may be either used as an alternative or not due to its minimal influence. Meanwhile, for the 2050s and the 2080s, different tree percentages (25% and 50%) show more potential PTC improvement. Thus, using 25% trees would be more rational, as this will not occupy significant pavement space; on the other hand, by applying 50% trees, there will be an insignificant thermal improvement in PET. By applying 50% of trees in EW in 2080, the thermal comfort level reaches an equivalent value to the EW canyon orientation in the 2018 base case with no UGS. This indicates an improvement in Ta and represents a potential shift back in climate by 62 years (to a 2018 climate). Alternatively, the thermal improvement in PET in EW by applying 50% trees appears to be comparable to the thermal comfort level in NS by 2050. Meanwhile, in the case of applying 50% trees in EW by 2050, the thermal comfort levels in EW would be equivalent to the thermal comfort level in NS in 2018. This confirms the significance of trees as being effective for mitigating the impact of climate change on thermal comfort.

3.2. Recommended UGS Alternatives for 2018, 2050, and 2080 Climatic Scenarios—Applying 25% Trees for NS and 50% Trees for EW

Based on the first stage of running simulations for different UGS within different climatic scenarios, the UGS alternative strategy was applied in each climate scenario to help recommend the most suitable and effective alternative for each canyon orientation within each scenario depending on the level of thermal improvement it affords to the pedestrians. Concerning the EW canyon, it was found that there was an urgent need for applying trees as a UGS alternative with 50% coverage within all climate scenarios, while within NS the 25% trees provided an appropriate solution to improve PTC within it. Thus, 50% of trees were applied in all years (2018, the 2050s, and the 2080s) within EW while, within NS, only 25% of trees were applied within those years. All climate scenarios were analyzed to investigate the outcome of the applied strategies. It has been found that for the most improved thermal comfort and climatic control of the 50% and 25% trees intervention, trees should not be aligned for more shade dispersed over the pavement; hence they improved thermal comfort across the canyon.

Figure 6a,b demonstrate that Ws benefited from the distribution of tree percentages across different canyons where NS naturally has lower Ws, so applying 25% would not significantly affect the Ws; hence, thermal comfort levels would still be within acceptable ranges. On the other hand, within EW, with higher Ws showing a higher thermal stress due to exposure to more solar radiation, the 50% trees option was the most appropriate alternative. Across different climate scenarios, Ws within NS was about 66%, 72%, and 68% of EW in 2018, 2050, and 2080, respectively. Overall, trees decrease Ws, yet they have improved thermal comfort due to their shading influence. On the other hand, RH decreased with time, yet trees increased the RH of the air by a small margin during dry summers. The increase in RH in EW has been found to be +0.87%, +1.34%, and +1.3% for 2018, 2050, and 2080, respectively. The Ws change percentage in Figure 6a also reflects an identical trend as the Ws graph in Figure 3.



(**a**) (**b**)

Figure 6. Wind speed (**a**) and relative humidity (**b**) for best alternative for each street orientation across 2018, the 2050s, and the 2080s.

Interestingly, after applying the most appropriate tree percentage for each canyon orientation for each climate scenario, the researchers reached the thermal comfort level balance between NS and EW. It has been affirmed that NS is a well-oriented canyon during hotter drier seasons since buildings block significant levels of solar radiation across the day; hence, there is less thermal stress on pedestrians. However, the EW canyon increases pedestrians' thermal stress due to the access of intense solar radiation across the day during summertime, as shown in Figure 7. Despite the fact that the PTC measurements are identical, on the map the PTC levels within PET, Tmrt, Ta, and Ts are almost the same with a negligible variation, as with NS the canyon lacks direct solar radiation after applying 25% trees in a staggered layout instead of being aligned as shown in Figure 8. The PTC measurements were consistent and stable across the whole canyon, as indicated in Figure 7. For EW, after applying the 50% trees, this has improved the PTC levels significantly and stabilized the thermal map (PET, Tmrt, Ta, and Ts) across most of the canyon, yet there were a few spots where the sun directly penetrates to the ground level without being blocked by trees.

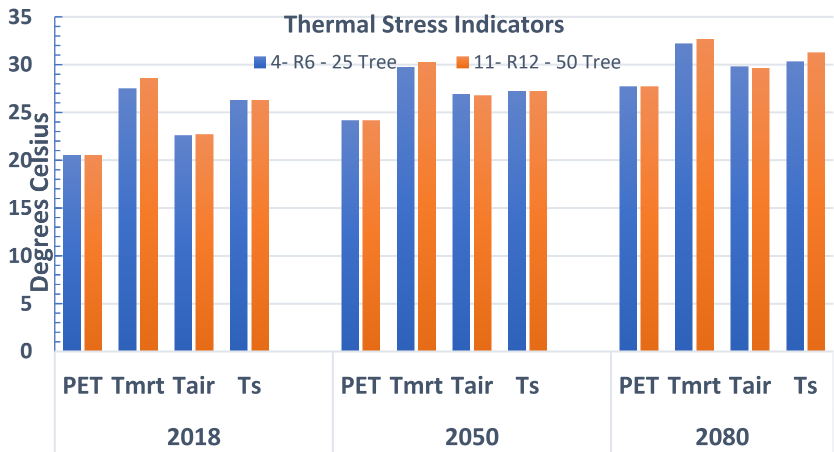


Figure 7. Thermal stress indicators for best alternative for each street orientation in 2018, 2050s and 2080s.

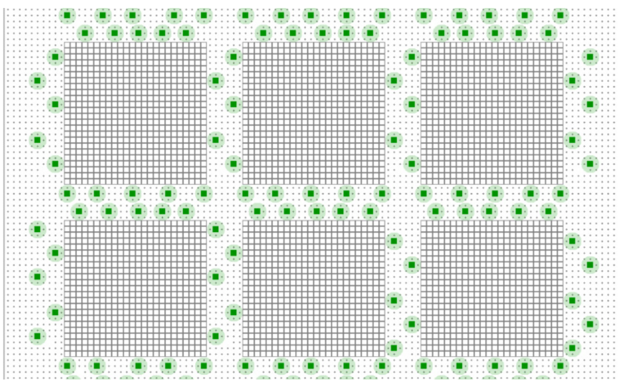


Figure 8. ENVI-met Spaces File showing shifted street patterns' design alternative: 25% for NS orientation and 50% trees for EW orientation.

4. Discussion

Over the course of the study, there have been comparable trends and outcomes to previous research (references to other studies) identified to support the impact of the UGS implementation within urban street canyons on mitigating the UHI effect [69]. Research studies recommend testing and developing innovative approaches for climate change adaptation and mitigation through incorporating UGS. In addition, it has been proven that UGS improve pedestrians' thermal comfort especially with the increase in shading ratio [70–72]. The present study indicates that the Ws percentage has decreased between 19.4% and 25% for different tree percentages across the three climate scenarios, which was similarly represented by [73]. Their study showed that Ws decreased around 20–80% for trees. Based on these points, it is worth mentioning that although trees tend to reduce Ws, they also improve thermal comfort levels due to increased shading, which outweighs the limitations of decreasing Ws. Figure 5, showing the PET of different years 2018, 2050, and 2080, indicates that by applying 50% trees within central London during the 2080s for the east–west-oriented street canyon, the thermal comfort achieved is equivalent to the thermal environment and Ta of the same street in 2018 without greening. Meanwhile, applying 25% of trees for the same canyon in the 2080s will improve the thermal environment and increase thermal comfort levels to achieve 2050s Ta without greening. Similar studies stated that after adding 10% more trees to Manchester, UK, this will reduce the UHI effect with the changing climate [37]. Furthermore, a recent study indicated that adding groves and street trees as a green cover to 10% could be the best adaptation strategy to significantly reduce overheating in Guangzhou, China [74]. A similar study was undertaken [75] during a typical summer day for current and future climatic scenarios (2030–2060) for Munich, Germany. This study simulated different UGS interventions (trees, living facades, and green roofs) for the urban neighborhood (street sidewalks, on parking lots, and in courtyards). This study tried to achieve two vegetation scenarios (realistic and maximum greening scenarios). The maximum vegetation scenario for each alternative was achieved through planting trees on sidewalks and in courtyards, greening flat-roofed buildings, and greening two-thirds of facades [75].

The aforementioned study in Munich, Germany, found comparable results to the London 2050 case of the current study; in which 22% (realistic tree coverage) and 34% (maximum tree coverage) caused a PET reduction of 10–13% compared to their base case scenario. While in London, the PET reduction varied between 9% and 21% for 25% trees, and 50% for EW canyons and 5% for NW canyons. On the other hand, for the PET reductions across each study, including the base case in year 2018 for London and year 2016 for Munich, the PET reduction between the different tree percentages was 4–7% in Munich. At the same time, it was around 5% in the NS orientation and between 11% and 14% in the EW canyons in London. Across both studies, some significant differences should be noted as a difference in geographic location, climatic data, and greenery percentages applied, yet the findings showed comparable patterns. However, these findings differed from another study [76], which stated that an increase of 20% green cover has led to a reduction in temperature that was up to one third or half of the expected additional UHI effect in 2050 in Glasgow, UK. However, the researchers discovered that both LF percentages (25% and 50%) bear a negligible influence on PET, although LF slightly increases RH. In their case study [75], they found that their LF had a PET reduction of 5–10%, but that is only closer to the building walls, while when pedestrians are more than two meters away from the building, there are no effects on PTC and PET, which was found by the current study in which the thermal receptors were set five meters away from the building [76]. This highlights the importance of LF coverage in insulating buildings and improving their thermal performance [77].

On the other hand, several studies [77,78] confirmed that green roofs (GR) have minimal/no influence to PTC even in future climate scenarios. This has clearly explained and investigated the influence of both living facades and green roofs on UHI and PTC, which confirmed that GR does not influence thermal comfort levels in the street levels, yet this influences the thermal comfort at a roof level, while LF influences the thermal comfort near the façade itself [24,31,79]. Even though achieving the UGS coverage of 30 to 50% is recommended by the findings from the literature review, in order to reach effective UGS interventions, there may be a need to combine UGS such as LFs, green roofs, and tree coverage. The improvements to thermal comfort are directly related to the UGS type, size, quality, and density. However, denser tree alternatives decrease wind speed, yet its thermal stress reduction benefits outweigh its windspeed reduction disadvantage, which was similarly found by [78,80]. On the other hand, the higher albedo pavement slightly increased the mean radiant temperature. However, it decreased the surface temperature which resulted in a significant increase in thermal stress, which was corroborated by another study [81], which attested that a higher albedo results in more incoming solar radiation; which is reflected into the street canyon, leading to a higher radiant temperature within the canyon. This outcome varied from findings of another study [51], which identified that high albedo materials within canyons enable a decrease in Ta and mitigate UHI effect in tropical climates.

Limitations of the Study

This research explored how cool pavements, green walls, and trees influence the urban heat island effects and mean radiant temperature in London. The methodology developed was a sequence of simulated environments in order to achieve and analyze the information, with physical monitoring. Some simulations might be insignificant or have no real influence on the process. UHI has significantly helped in achieving a wider overview and a better understanding of the procedure and outcomes. The simulated environments might be limited due to their size, function, scale, and physical models' materials. Due to time constraints, it was not possible to use different UGS types with different changes, such as the foliage leaf thickness, type of green wall used as a green façade, intensive green roofs, and basic street trees, to name a few.

Moreover, insufficient weather data from central London, except for Heathrow Airport, hindered accurate climate predictions for 2050s and 2080s. UKCP18 lacked hourly weather data compared to UKCP09, despite similar predictions. Simulations were constrained by time, preventing diverse Urban Green System (UGS) types and necessitating a common practice.

The main research method is the ENVI-met modelling software which normally includes some form of simplification and abstraction, leading models to be an approximation of the reality. Hence, ENVI-met's simplification limits the accuracy, representing Physical Thermal Comfort (PTC) scientifically but neglecting psychological aspects. ENVI-met lacks nuances in Vertical Greening Systems (VGS) and the Living Façade (LF) impact on CO_2 sequestration. CO_2 assumptions for 2050s and 2080s lack Met Office data. The study focused on Surface UHI (SUHI) without considering night time SUHI or UGS impact on different UHI levels. The ENVI-met software scientifically portrayed the Physiological Equivalent Temperature (PET) by illustrating variations across diverse alternatives, capturing physical enhancements. Nevertheless, it failed to depict the emotional and psychological improvements experienced by individuals when encountering and engaging with nature in actuality. For instance, the question arises whether the increased presence of trees or green walls in streets contributes to the enhanced thermal comfort for individuals, irrespective of tangible thermal improvements.

Lastly, the study overlooked UGS effects on air pollution, as it focused on the thermal impact of the UGS at human scale, neglecting the neighborhood, seasonal variations, and economic considerations. Moreover, different UGS species' cooling capacities, application costs, and time required (for fitting and maintaining) were unquantified. Despite the above limitations, the methods, subjects, and instruments applied achieve a relative balance between feasibility and generality.

5. Conclusions

This study has been undertaken in an effort to investigate UGS as an approach to mitigate the impacts of and adaptation to climate change. It aimed to provide recommendations that could be applied within street canyons to reduce pedestrians' thermal stress. The purpose of this is to encourage individuals to adopt a more active lifestyle, improve their quality of life, increase biodiversity, increase visual comfort and connecting to nature in addition to improve the thermal comfort in outdoor spaces. The use of vegetation in poorly oriented, dense canyons may compensate for the shortcomings of their design and orientation, particularly in high emission scenarios versus low emission scenarios. This becomes more evident in the 2080s followed by the 2050s and in 2018 due to its higher UHI effect; meanwhile, if it has been applied to the whole city scale, a more significant improvement for the UHI effect could be reached at an urban scale.

The study investigated the application of LF 25% and LF 50%, where a reduction of −1.17 °C and −0.09 °C, respectively, were found as a Ta, which is almost negligible for LF 50%. Notably, in the 2050s climate scenario, the overall temperature rose by almost 3 °C, taking into consideration that applying 25% trees in the NS canyon becomes more crucial to increase PTC. Meanwhile, for the EW canyon, at least 50% trees would be needed due to the higher solar radiation and higher Ta within an EW orientation. Concerning the NS canyon, 25% and 50% trees achieved a similar thermal improvement due to the lack of direct solar radiation, where both saw around a 2 °C decrease in PET. Meanwhile, for the EW canyons, 25% and 50% LF have a negligible effect on PET. Results indicate that HPA has increased heat stress in both NS and EW canyons, as it reflects solar radiation into the canyons, which asserts that the position of placing the UGS intervention is a crucial factor in its efficiency and benefit. For EW, 25% and 50% trees reduced Ta between 2.8 °C and 6 °C (10 and 20% improvement in PET), respectively; nevertheless, an insignificant improvement was found of 0.04 °C and 0.19 °C for 25% and 50% LF, respectively. The 2080s climate scenario had a similar pattern to 2050 in terms of the UGS efficiency in both canyons, yet it shows more importance as the heat stress increases, where HPA in NS has increased PET by 5 °C and 10 °C in EW canyons. Meanwhile, 25% and 50% LF have a negligible influence; both trees' percentages slightly improved PET by 2 °C maximum in the NS canyon, causing a thermal improvement to shift significantly in the EW orientation by a −4 °C reduction for 25% trees and −9 °C for 50% trees.

Vegetation type, canyon location, and percentage exhibit a heightened efficacy in warmer temperatures and lower humidity, which is evident throughout 2018, in the 2050s, and in the 2080s climate scenarios. Trees demonstrate a maximal temperature reduction, while LF contributes to an increased humidity with a limited impact on Ta. Shading proves the primary benefit of UGS in adapting to and mitigating heat stress, with their subsequent role in carbon capture and storage. This underscores the substantial thermal benefits of trees over LF and HPA, which lack shading capabilities. Conversely, building shading, particularly in NS orientation, serves a pivotal role by obstructing GSR, casting shadows, and reducing the reliance on UGS. LF's impact on UHI is negligible, as solar radiation primarily impacts the street canyon rather than building facades, especially in the EW canyon orientation. Despite the LF-induced humidity elevation, further examination is warranted to assess potential repercussions on building energy performance and its influence on thermal comfort within urban canyons.

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