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The Influence of Urban Green Systems on the Urban Heat Island Effect in London

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Abstract. Urban areas are typically warmer than rural ones. This is mainly due to denser configuration dominated by impermeable surfaces such as buildings and roads, compared to rural areas which are less densely built and mainly dominated by open spaces. Rapid urban expansion in dense cities bares direct impact on surface and air temperature patterns within street canyons; a phenomena which is known as the Urban Heat Island (UHI) effect. Thus, several UK city councils such as Birmingham, Manchester, and London have started to develop strategies aiming at enhancing urban green systems (UGS) through trees, green walls and green roofs. Some of those strategies include considering the green space factor, and increasing green areas within the cities to improve street canyon microclimate and reduce UHI. The Mayor of London has adopted a strategy for London 2050 aspiring to transform it to be the greenest city in the world by increasing the green areas up to 50%. This paper investigates the influence of increasing the UGS percentage which is considered as a key solution to mitigate UHI effect which will, in turn, provide thermally comfortable outdoor environments for pedestrians. The investigation is undertaken by comparing the morphology of precincts and streets in relation to air temperature, mean radiant temperature and surface temperature within Oxford Street canyons in London city centre; being one of the world's busiest streets. The results from this research demonstrate that different UGS interventions with varying percentage are required depending on particular canyon orientations and geometries. The study found that, in general, more trees would have significant thermal comfort effect followed by living façade, while high albedo pavement (HAP) came last. However, HAP had high influence on improving thermal comfort in North-South orientated streets with minor variance to trees and living facades which, changing their percentage levels was insignificant.

1. Introduction

Global cities are currently inhabited by almost half of the world's population, which is expected to increase by 70% by 2050 [1]. The UK has more than 60% of its population living in cities, while most European countries have almost 50% living in cities [2]. Thus, the higher population densities, the higher the impact of climate change [3]. Climate change and associated heat waves may increase the number of heat-related deaths in Europe from 152,000 to 239,758 a year by 2080, leading to 50 times death rise, while in the UK nearly 11,000 persons may die every year as a result [4].

Depending on relative vulnerabilities of the population, infrastructure, ecosystem, etc.; the impact on cities may be diverse [5]. Since London's streets and pathways contribute by up to 80% of London's public spaces [6]. Thus, policy makers are establishing climate change programs that require architects, planners and urban designers to integrate climate resilience in refurbishment, retrofitting and newly built developments [7]. There have been various calls for interventions initiated in the UK, in response to climate change adaptation and mitigation on the urban scale level as Healthy Streets for London by Transport for London (TfL) [8], London Environment Strategy, London Urban Heat Island, London Infrastructure Plan 2050, and Urban Green Factor by Greater London Authority (GLA) [9–14]. On the other hand, there have also been some initial design proposals to address this issue; such as Walkable London by Zaha Hadid Architects [15]. Notably, Adaptation and Resilience in a Changing Climate (ARCC) research network for different scales and level projects, has evolved to develop adaption analysis tools for urban areas, focusing on the built environment, infrastructure, transportation system as the main objective for effective climate change mitigation initiatives [16, 17].

The current study addresses an important topic of assessing the influence of UGS on mitigating UHI since UGSs may help minimise cooling and heating loads and overall operational energy demand within buildings. The research investigates how green roofs, trees and vertical green systems (green walls and living façades) may potentially mitigate the adverse effects of climate change, by lowering the UHI effect and improving pedestrians' thermal comfort.

2. Research context

2.1 Urban Heat Island (UHI) in London

UHI is the phenomenon at which air temperature in cities would tend to be higher than the rural areas of close proximity during warmer seasons particularly during night time [18]. The UHI occurs due to solar energy storage within the urban fabric accumulating during the daytime, which is then released back to the local environment during night time. When green spaces are being replaced by buildings and roads, the thermal, radiative, moisture and aerodynamic properties of the surface and the atmosphere change (GLA, 2006). UHI bears a direct effect on London's climate leading to warmer winters, earlier spring season and less snow. The UHI effect leads to approximately 2°C warmer temperature during the night and -0.2°C cooler temperature during the day leading to UHI intensity reaching up to 9°C in 2003 compared to only 4-6°C by 1960 in London compared to surrounding rural areas [10]. It is expected that summer air temperatures in the South East of the UK may rise by 3.5°C, and 5°C by 2050 and 2080, respectively [19]. London City centre may also face up to 9°C in air temperature compared to the surrounding greenbelt with expectations to the frequent increase of heat waves [10]. London UHI mitigating strategies must be developed coherently between key stakeholders; urban planners, climate change scientists, and policy makers. Thus, in developing mitigation strategies for London's UHI, it must be considered that the UHI is a city scale phenomenon and the outcome of the combination of the vast range of microclimates that occur across London.

2.2 Urban Greenery Systems for UHI mitigation

A classification system of UHI mitigation strategies has been recently established [20] grounded on grouping the measures according to selection criteria of action-oriented adaptation which aligns with the shared and mutual view of policy makers. This system led to categorising UGS interventions into 4 main scales: urban landscape, street geometry, building envelope and pavements. Consequently, 11 mitigation strategies have been identified to mitigate UHI; namely: cool building envelope, green roofs, green facades, ground vegetation, shading trees, cool pavements, water bodies, water-retentive pavements, built environment orientation, built environment prevailing winds, built environment orientation built environment typical section and built environment orientation to the sun [20].

Urban greening is much more than a luxury or an aesthetical intervention for cities. It needs to be considered as a vital part of urban planning [21]. Thus, the GLA recommends a few measures to manage UHI in London [10]. Firstly, urban greening as trees, parks is an effective way of enhancing and improving harsh urban climates throughout individual buildings within the neighbourhood scale, due to evapotranspiration process and reducing surface temperatures between 5-20°C due to shading. It is also very important to consider the type of tree canopy in order to avoid trapping air pollutants from the street [18]. Secondly, living façades, green walls and green roofs (GR), which include a growing medium planted above a waterproof membrane, might potentially have an influence on the atmosphere around it and on the building fabric (walls) insulation, while GR has an influence on the upper floors of buildings in the green roof case [22–24]. Lastly, fixing cool pavements with high reflective solar material and water preamble will help in high urban temperature mitigation through rain storage and reflecting high solar energy rates [25]. The current study will be mainly focusing on trees, living walls and high albedo pavements (HAP).

3. Research Methodology

The main aim of this study is to investigate the extent to which UGS may play an effective role in the mitigation of the UHI, in the current and future climate scenarios using Oxford Street in London as the case study. The research methodology is primarily quantitative; applying ENVI-met software for modelling and on-site measurements. The paper focuses on ENVI-met modelling and data analysis. Envi-met was developed at Ruhr-University Bochum in Germany [26]. ENVI-met software package facilitates modelling the microclimate effect of vegetation and its influence on UHI, Physiological Equivalent Temperature (PET), Air temperature (Ta), Radiant Temperature (Tmrt) and Predicted Mean Vote (PMV). Thus, the tool helps undertake the investigation of the impact of UGS on the microclimate.

3.1 Model Geometrical Specifications/inputs

The main criteria for deciding the case study is to choose and model some of the most polluted and highly populated streets in the UK [27] as a worst case scenario. Hence, central London's Oxford Street was chosen as the research case study where many of the aforementioned challenges exist. The canyon between Orchard Street and Park Street, characterised by Height: Width of 1:1 while the length of the building block is 120m and the street canyon is 140m as illustrated in Figure 1 with a total neighbourhood area of (520mX520m).

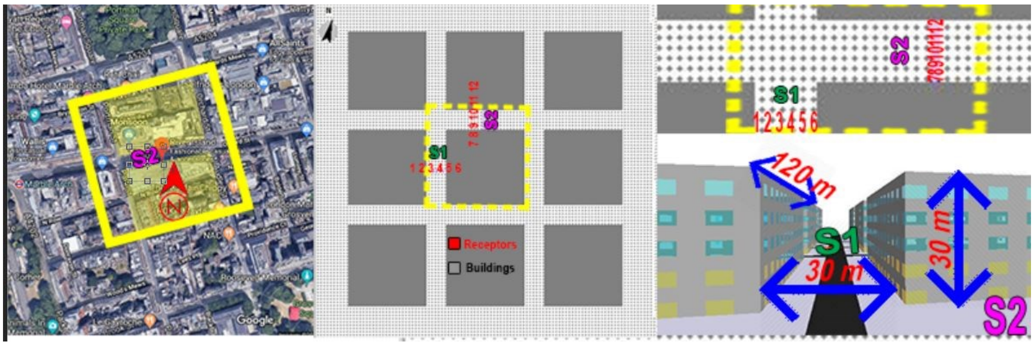

Figure 1. Oxford street (left), Street 1&2 layout with receptors locations (middle), Receptors locations (up) & Model dimensions bottom (right) (Source: Google map, ENVI-met)

Several studies [28, 29] have asserted that similar canyons dimensions need to be investigated for the purpose of improving pedestrians' thermal comfort (PTC), especially during the summer season[28, 29]. Thus, measurements are taken within the North-South (NS) street (S1) and East-West (EW) street (S2) as shown in Figure 1 (middle picture) which represents the Oxford street case. This would also be for the middle canyon within our middle neighbourhood. Since it represents the real canyon within central city urban fabric figure. Measurements are taken at the location of 6 Receptors (R) located in the middle of each canyon (total of 12 Rs in both canyons as in figure 1 middle). The physiological equivalent temperature (PET) is used to determine PTC as it uses the skin of the human body to calculate all energy exchanges, core temperature and sweat rate while considering clothing as a secondary variable [30].

3.2. Modelling scenarios

In order to evaluate the effectiveness of the proposed UHI mitigation scenarios in relation to PET, the real empirical model will be testing the following scenarios as illustrated in Fig 2. Two different green system types; trees, living façade (LF) are then incorporated at two 25 and 50 percent. High pavement albedo (HPA), such as white concrete (Albedo=0.8), is also tested with 66.6% of canyon area, which represents all pavement area. It must be noted that the vegetation in central London is almost negligible in main streets, whilst in the case study canyons is negligible, hence the base case setting was fixed at 0% vegetation.

The simulations are then undertaken for the four different scenarios; base case, trees, living facade (LF) and pavement albedo using 2018 Met Office climatic data in order to evaluate their influence on UHI mitigation by using the 12 Receptors. The two different ratios for each vegetation type is then applied, by increasing the current case by (25% and 50%). The Greater London Authority (GLA) [9, 12] plans to upsurge the green areas in London from 38.4% to 50%, hence applying 50% as the maximum level of vegetation.

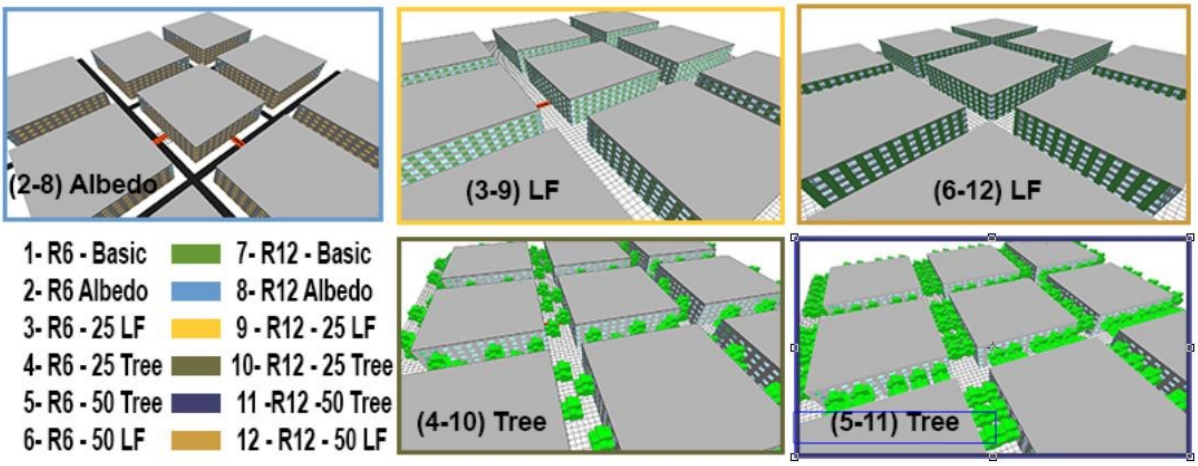

Figure 2. UGS alternatives (legend colours represents different UGS alternatives')

4. Results and Discussion

After running simulations for Oxford Street canyons previously identified, results were extracted from ENVI-met in the form of graphical illustrations and numerical excel files from the Receptors within both canyons. Street 2 (S2) represents Oxford Street while Street 1 (S1) represents Regent's Street which intersects S1. The different vegetation and albedo strategies were applied to determine which intervention(s) are more appropriate to be used within the case study canyons to improve pedestrians' thermal comfort. Thus, PET, PMV, Predicted Percentage of Dissatisfied (PPD) have been the focus of the study. Further analysis is undertaken to explore how Ta, Tmrt, Surface Temperature (Ts) Wind Speed (Ws) and Relative Humidity (RH) influence pedestrians' thermal comfort (PTC).

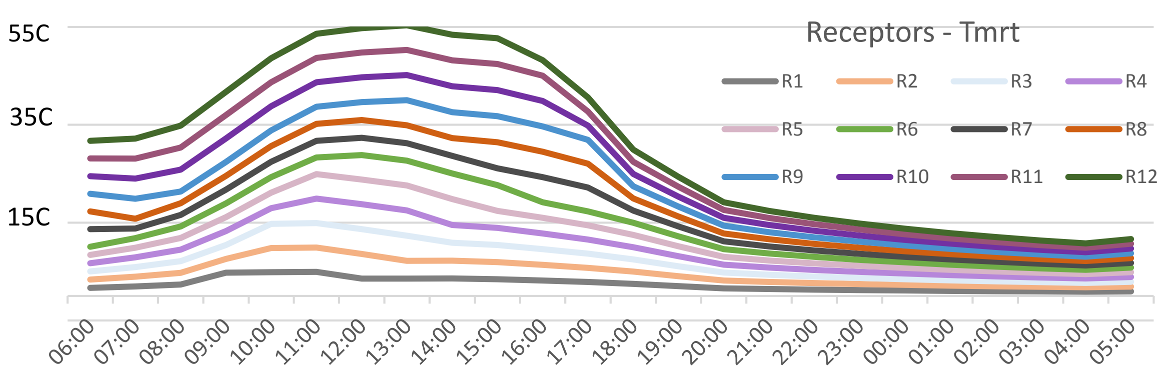

Figure 3 Mean Radiant Temperature (Tmrt) Measurements of the 12 receptors (Source: ENVI-met)

As shown in Fig. 3, the Mean Radiant Temperature (Tmrt) at all 12 Receptors have been extracted for the average of the summer season in 2018. However, as there have not been significant differences between Tmrt and Tair at each receptor, the highest value of each street receptors based on PET and PMV has been chosen to represent the canyon (S1, and S2), those being R6 and R12. Consequently, PMV and PET were measured to determine which time of the day has the maximum heat stress, which was found to occur at 16:00. Thus, further heat stress indicators (PET, PMV and PPD) and calculations regarding UGSs and albedo effects are then undertaken.

4.1 Thermal Comfort Values (PET, PMV and PPD) at Street 1 and Street 2

Figure 4 demonstrates the calculations at R6 and R12 concerning the PET, Ta, Tmrt and Ts. It was clear that the Ta had no notable variance with the changing strategies. However, UGSs had a significant influence on both Ts and Tmrt which have reflected on PET. Thus, PET was used as a clear indicator of pedestrians' thermal comfort within street canyons based on other outputs as Ts, Tmrt, RH and Ws. Overall, in S1 (north-south) UGS was not as effective as in S2 (east-west) due to higher solar radiation and higher sun hours associated with S1 orientation and canyon geometry. Hence, altering pavement albedo would be a feasible and cost-effective solution, particularly for the Ts. Shading pavements have been the main reason for lowering temperature due to blocking access of solar radiation to the pavement surface and hence improving pedestrians' thermal comfort level.

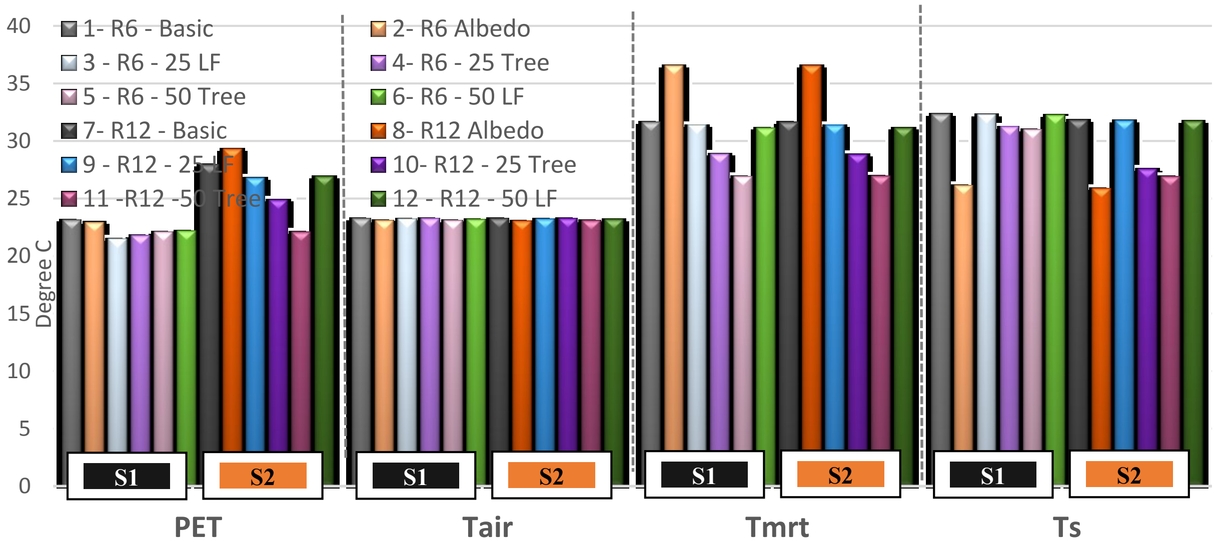

Figure 4. PET, Air Temperature, Mean Radiant Temperature and Surface temperature comparison (Source: ENVI-met)

It was not as effective to change the UGSs percentage for either trees or Living Facades (LF) where the maximum reduction in PET was -0.3 °C which means, increasing trees up to 50% may not be an effective (nor feasible) solution. While it was -0.67 °C for LF where walls have been receiving higher solar radiation and hence more temperature variations were found. For S2, trees have been more practical in improving PET comfort levels where there has been a difference which was observed between 25 and 50% trees which reached -2.76 °C. While surprisingly PET increased +0.14 °C when LF percentage increased from 25 to 50%, where RH might be the main driver for that, however, Ta lowered slightly in R12 and Ts and Tmrt had a similar pattern to R9. High surface albedo was increased heat stress by +1.36 °C for PET than the basic case, however, it has decreased Ta by -0.20 °C and by – 4.91 °C for Ts and increased Tmrt by +5.42 °C.

Interestingly, the percentage of reduced PET due to UGSs in S1 street had a similar pattern were using 50% of either trees or LF had same -1.04% while similar reductions found 1.06 and 1.07 from trees and HAP. While for S2 Street, both LF of 25 and 50% had almost the same PET reduction of -1.04% and -1.03% respectively. The higher saving percentage was found for trees with 25% and 50%

reached -1.12% and -1.26% correspondingly. These percentages could be used to give us indications about how UGSs act to heat stress in the cloudy would or a cooler day or in winter for instance based on S1 Street.

4.2 Relative Humidity (RH) and Wind Speed (Ws)

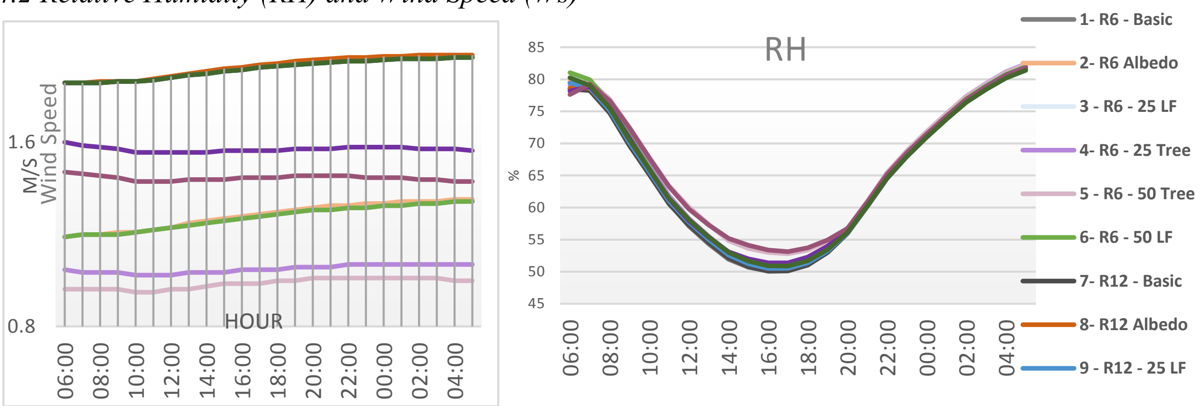

Figure 5. Wind Speed (left) and Relative Humidity (right) comparison (Source: ENVI-met)

In Figure 5 for S1, wind speed ranged from 1.1-1.3 m/s across the day while with negligible changes for both LF percentages', which was 1.12- 1.28 m/s. For the two tree percentages, the wind speed reduced to 0.99-1.01 m/s for R4 and 0.92-0.95 m/s for R5 which clearly shows that trees have blocked even the low wind flow.

For S2, wind speed ranged from 2-2.2 m/s for all cases except the R4,5 with trees at which trees have significantly reduced the Ws in R5 from 1.6-1.55 m/s and 1.43-1.38 m/s in R5. This could show us great evidence that in-case a higher wind speed, a higher thermal comfort would have been expected during the hot season. Although trees have lowered Ws, the highest thermal comfort was met in PET. For RH in S1 and S2, it had the same pattern across different UGSs however Rs near trees or vegetated walls might have felt a slight difference. Higher RH was noticed in S2 than S1 especially for R12 followed by R11, R10, R9 and with the same vegetation sequence at S1.

4.3 Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)

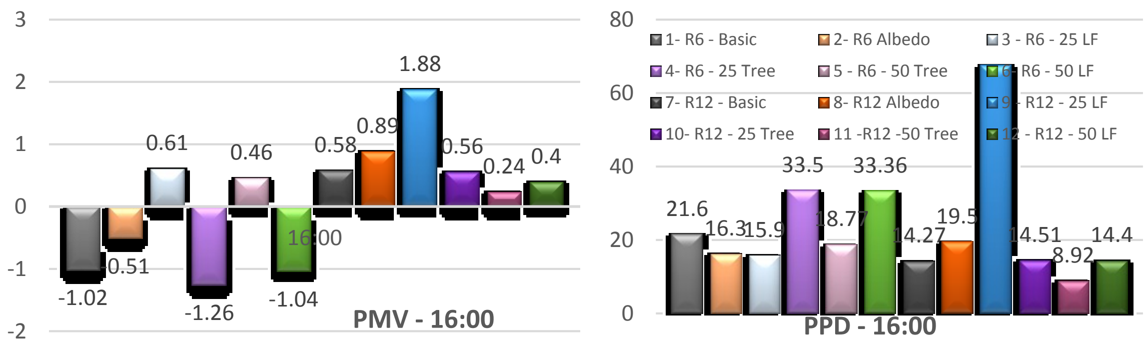

Figure 6. PMV (left) and PPD (right)comparison (Source: ENVI-met)

Figure 6, PMV and PPD have a linear relationship where PMV calculations are based on (Ta, Tmrt, Ws and vapour pressure) where its assumptions were mainly for steady-state indoor situations with extending the energy fluxes with long and short wave radiations in order to use it outdoors [30]. For S1, using higher albedo material, 25 LF and 50% tress have to lead to change PMV positively from cold to slightly cool and slightly warm for R4 and R5. While it was cooler when added 50% LF and cooler for 25% trees. For S2, UGS has improved PMV from warm to slightly warm, except at R2 and R3 where R3 has increased massively to be hot.

PMV seems not the following PET, Ta and Tmrt follow a similar trend, which might be due to PMV considers the effect of clothes and human activity into consideration in a scale, not in a numerical number, which might have several interpretations. For instance, adding lighter clothes within the warmer street canyon would lead to higher discomfort levels, that's due to increasing the skin surface facing the sun, however, it is more logical that it should be more thermally comfortable. As for PPD; in S1 around 33.5% of people felt discomfort at R10 and R12 however it is still acceptable. While in S2, 67.6% of people have been dissatisfied which also demonstrates that there is a linear relationship between PMV and PPD [30].

5. Conclusion

A relationship between UGS and UHI mitigation in the current climate scenarios of summer 2018 is being established using numerical methods through addressing this knowledge gap in this field in order to determine the most influential factors affecting pedestrian thermal comfort. Being able to decide whether increasing UGS percentage would likely to increase the PTC or not. On another hand, the location and the way of UGS placement are more vital and responsible for increasing PTC.

UGSs implementation within London city centre would be different in terms of the type of UGS, its percentage, where it is applied and that would be based on street orientation where S1 streets does not need much vegetation as S2 streets that is mainly due to solar radiation and the buildings height within the canyon limits sunlight rays to reach street level due to building shading. For S1 street, applying high albedo surfaces for pavements would increase comfort through reducing PET by 0.21°C. The latter was due to its high effect on lowering surface temperature while its reflectivity had increased Tmrt. while other vegetation percentages, PET improved by -0.35 to -1.05°C. With regards to S2 canyon, a very high thermal stress was found compared to S1, HPA increased thermal stress by 1.3°C due to its high Tmrt, while trees lowered PET by 3.08 and 5.84°C for 25% and 50%, espectively. While for LF 25% and 50%, -1.17℃ and -0.09℃ was found as a Tr which is almost negligible for LF 50%.

Concerning Tr percentages in PET, it could be concluded that with cooler temperatures across the year seasons and days, similar savings in Tr percentages were similarly found based on S1 and S2 comparison where S1 has a well-oriented canyon and has low direct sun hours. PET was a more precise way to indicate thermal stress and thermal comfort since it considers the effect of several variables on human skin: Ta, Tmrt, Ts, Ws, RH, and solar radiance. Trees reduce Ws slightly but do not influence thermal comfort as Ws is already too low. However, they work better in higher solar radiance and challenging orientations of streets. Increasing LF and trees percentages raise RH levels, especially LF.

Notably, HAP type has a huge influence on surface temperature while it has a higher Tmrt as well, thus it is advised to be applied in NS streets which lacks direct sun light and high radiance as well. PPD has been lowered in all UGSs alternatives even in HPA case which had higher PET before, while it increased in 25% LF case up to 67.6% in EW Canyon. That might be because PMV and PPD do not take solar radiation and Ws into consideration, while it considers humidity and activity of pedestrians and their clothes.

Overall, HPA and low vegetation work better for NS canyons and higher vegetation percentage especially trees which are more pedestrian friendly in reducing thermal stress during summer days. While for EW canyons, trees are more advised for higher thermal comfort especially with a higher percentage. Thus, it might be advised to use HPA with another strategy which offers to shade such as trees for instance.

Trees have been more effective during extreme heat condition, due to their shading effect in the first place as well as their direct influence on pedestrians rather than LF. This has more influence on building fabric and it only makes a difference when solar radiation falls over it which is not occurring in our case in central London with narrow canyon. The results of this study provides an in-depth understanding of the potential of UGSs to mitigate the UHI effect in a sustainable, energy-efficient and cost-effective way. However, it is recommended to carry out further numerical simulations to estimate the extent to which UGSs may help mitigate climate change in future scenarios of 2050s and 2080s.

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