Asymmetries in Urban Weather Generator for Climate-responsive Design

The effect of vegetation on urban heat island

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The Urban Weather Generator (UWG) is a widely utilized tool for modeling the influence of urban fabric on climate variables, recognized for its reliability. However, recent studies suggest limitations in its ability to accurately represent the effects of vegetation, particularly trees. This paper evaluates the potential and constraints of UWG, comparing versions 4.1 for Matlab and the Grasshopper plugin Dragonfly. Real and hypothetical scenarios with significant vegetation increases were analyzed, revealing the model's limited sensitivity to vegetation changes in dense urban settings. Simulations showed minimal air temperature variations indicating that while other parameters influence the Urban Heat Island (UHI), the limited representation of vegetation restricts its application in design scenarios. The difficulties in assessing the effect of greenery on the urban microclimate do not seize the opportunity of digital tools to propel performance-based climate-responsive design.

Keywords: *urban heat island, sensitivity analysis, urban vegetation, urban microclimate, UWG*

INTRODUCTION

The Urban Heat Island (UHI) effect is a significant environmental concern leading to elevated temperatures in urban areas, and resulting in increased energy demand for cooling, worsened air quality, and health risks, particularly during heatwaves. The escalating global climate crisis intensifies these impacts, underscoring the urgency to thoroughly understand the characteristics of UHI and develop effective solutions to mitigate its effects and promote thermal resilience in cities.

In recent years, significant efforts have been made both to develop digital tools for advanced simulation of the urban climate and in support of performance-based design methods. In response to enhancing thermal comfort and promoting climate resilience design and planning practices, there is an increasingly demand for easy-to-use tools suitable for being included in the design workflow at urban and building scales.

Most of these simulation tools become accessible and readily available to a wide number of designers with diverse education. On the one hand, this is producing a shared awareness in professional practice of the complex interactions occurring in the built environment and their effect on energy and environmental issues, on human comfort and health in light of climate emergency. On the other hand, it raises a question about the reliability of these tools and the associated simulation results by non-specialists, without a scientific background on the matter or any formal education. Moreover, to this matter, there is too little design culture in these individuals that would permit a proper integration of physics-based tools in the process without compromising the creative process.

Among these simulation tools, the Urban Weather Generator (UWG) is one of the most used, recognised for its reliability in modelling the effect of urban fabric on urban air temperature and informing the design of urban microclimates. Its physics-based approach allows for the simulation of complex energy exchanges within urban environments, offering insights into the UHI effect at the neighbourhood scale. A key advantage is its computational efficiency, offering a balance between complexity and usability.

Specifically, the Urban Weather Generator (UWG) incorporates four principal modules. The Rural Station Model (RSM) computes rural sensible heat flux from meteorological data. The Vertical Diffusion Model (VDM) derives vertical air temperature profiles above the rural site, utilising data from the RSM. The Urban Boundary Layer Model (UBLM) estimates air temperatures above the urban canopy layer, informed by the RSM and VDM, and considering advection effects. Finally, the Urban Canopy and Building Energy Model (UC-BEM) simulates street-level urban weather and building energy consumption, employing the Town Energy Balance (TEB) scheme and incorporating anthropogenic heat and building physics. These modules are coupled to model urban microclimates and work to morph a rural EPW file to approximate urban climate conditions. It is important to mention that UWG algorithms are based on the energy balance in the 2D canyon geometry, which is calculated in a simplified way from the input morphological parameters (Bueno et al., 2013). For this reason, the results are more accurate for homogeneous urban fabrics with canyon-like street geometries, while they may be misleading for highly heterogeneous urban areas with varying building heights and openness of the urban fabric (Salvati et al., 2019).

The UWG model has seen development across different versions and platforms. The core of UWG is described as a stand-alone program with open-source code available in MATLAB and Python under the MIT License. These open-source versions allow for customization and integration with other tools. The more extended and updated functionalities, including the enhanced graphical interface and coupling with design software like QGIS and Rhino/Grasshopper (via plugins UMEP and Dragonfly), are also available as open-source software under licenses like the GNU General Public License. This ensures accessibility, encourages community-driven development and streamlines the assessment of UHI within the design workflow, establishing it as a valuable tool for performance-oriented climate-responsive design.

LITERATURE REVIEW AND RESEARCH GAP

The UWG is employed for analytical purposes in generating hourly estimations of urban canopy air temperature and humidity at the neighbourhood scale, providing insights into the intensity, gradients and diurnal patterns of the UHI (Mao and Norford, 2021; Nakano et al., 2015). Furthermore, UWG has been applied to investigate the impact of various urban parameters on the local thermal environment, including sensitivity analyses to determine the relative influence of different input parameters on urban air temperature and energy consumption (Nakano et al., 2015; Mao et al., 2017; Salvati et al., 2019; Xu et al., 2022).

Beyond its analytical capabilities, UWG is being integrated into design processes to identify and evaluate different scenarios or strategies for mitigating the UHI, and reducing building energy demand (Nakano et al., 2015; Hashemi et al., 2024; Kim, Gu and Kim, 2018). By allowing users to input and modify neighbourhood-scale planning parameters, such as building density and tree canopy coverage, UWG can simulate the resulting changes in thermal environment conditions. Despite its advantages over other urban canopy models, UWG exhibits several limitations in both analytical and design applications. While significant efforts have been made to enhance the user interface and integrate UWG with user-friendly platforms like Rhino (previously), Grasshopper (recently) and the UMEP plugin in the QGIS environment, a fundamental understanding of urban climate principles and the underlying model structure remains crucial for effective use and interpretation of results – particularly regarding energy fluxes. However, the development of visual scripting environments and pre-set default values aims to lower this barrier for non-specialist users.

Although this acknowledged ability to generate urban meteorological files, previous studies show that the model lacks reliability and the effect of vegetation and trees seems to vary case by case. Sensitivity analyses conducted on UWG have yielded varied results regarding the influence of vegetation parameters. While some studies, such as those in Basel (Bueno et al., 2013), Barcelona and Rome (Salvati et al., 2019) and Toulouse (Hamdi et al., 2024), reported sensitivity to vegetation parameters, the sensitivity analysis conducted for Abu Dhabi indicated that vegetation variables had an irrelevant impact on the model output (Mao et al., 2017). This discrepancy likely stems from the specific urban context, particularly the sparse vegetation cover in Abu Dhabi compared to the European cities. The study over Toulouse also noted that surface parameters, including vegetation cover, had a smaller influence compared to atmospheric variables. These findings suggest that the impact of vegetation parameters on UWG simulations can be context-dependent and may be less pronounced in environments with limited vegetation. Recent studies have overcome some of these limitations by implementing new features or extending UWG capabilities (Xu et al., 2022; Moradi et al., 2021; Moradi, Krayenhoff and Aliabadi, 2022). However, these features are not available in the widespread design tools available to date and are commonly used for understanding the effect of vegetation in UHI mitigation.

The vegetation's role and the capability of simulating the associated mitigating effect of UHI in the design process is particularly important nowadays, as many cities as facing major problems with overheating and climate change and are trying to react by means of Climate or Forestation Plans where the role of vegetation is crucial.

Figure 1
Aerial view of the two case studies

Therefore, reliable and easy-to-use design tools able to assess these effects within different urban fabrics are essential. This paper discusses potentialities and constraints of UWG in this context, highlighting the asymmetries between the ever-growing tool application in climate-responsive design scenarios and users' awareness in interpreting the results.

METHOD

To assess UWG sensitivity to vegetation parameters and the effects on UHI, the city of Barcelona has been selected as a real-case reference. In particular, the tool has been tested on two different neighbourhoods: Raval and Sant Martí.

Table 1
Case studies built-form parameters

Raval	
Average Height	17,2 m
Footprint Density	0,59
Façade to Site	0,95
Sant Martí	
Average Height	24,8 m
Footprint Density	0,21
Façade to Site	0,95

The selected neighbourhoods represent different morphologies typical of the compact city. Raval is characterized by high-compactness and mid-density urban fabric, with narrow streets and mid-rise buildings. Moreover, the presence of vegetation is particularly low. Conversely, the urban fabric of Sant-Martí – an XX-century district on the outskirts of Barcelona – is characterized by low compactness and by the presence of high-rise buildings. The parameters representing the urban morphologies are reported in Table 1.

Three different scenarios were compared to test the model's sensitivity to the presence of vegetation. Firstly, the simulation was run for the existing scenarios, using the real vegetation characteristics as input parameters. Secondly, an ideal case, named "All Green Scenario", in which all the free surfaces are covered with grass and trees and all the roofs are assumed to be green roofs was tested. Finally, a second ideal scenario, named "No Green Scenario", in which the vegetation was removed was run. The specific simulation parameters are reported in Table 2.

The Typical Meteorological Year (TMY) EPW weather file from Barcelona El Prat airport was used as input rural weather data for the simulation. Results are presented with hourly variations for the hottest week of the year and the entire year. The study compares the UWG 4.1 Version for Matlab and the UWG for Grasshopper plugin Dragonfly. Finally, the simulation ran for the two neighbourhoods in the three different scenarios and the results were compared and discussed

Table 2
Case studies vegetation parameters

	Raval		
	Existing	All Green	No Green
Tree Cover	0,12	0,41	0
Grass Cover	0	0,41	0
Roof is Veg	0	1	0
	Sant Martí		
	Existing	All Green	No Green
Tree Cover	0,45	0,79	0
Grass Cover	0,07	0,79	0
Roof is Veg	0	1	0

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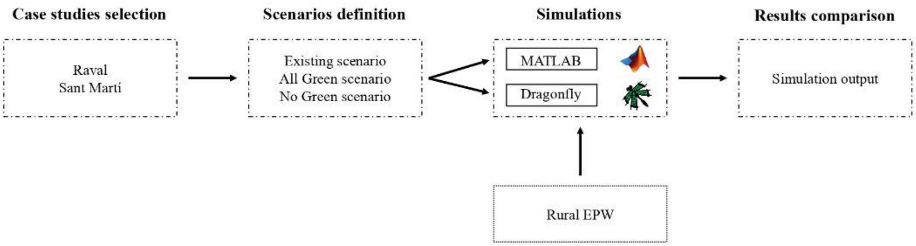

Figure 1
Workflow showing the steps of the methodological framework

RESULTS AND DISCUSSION

The air temperatures calculated by UWG for the two case studies for the hottest week are reported in Figure 2.

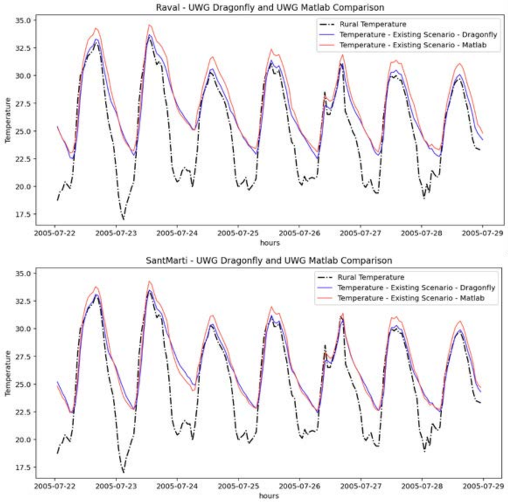

Figure 2
Case studies comparison in real condition

These results consider the current conditions of vegetation for the two areas. In both cases, UWG estimates a pronounced UHI intensity during the night hours, reaching an average maximum intensity of more than 5°C at 1 am.

The figure compares the results for the MATLAB and Python-Dragonfly versions, highlighting some differences between the two models.

The MATLAB version returns higher average UHI intensities. In Raval, the average weekly UHI is 2,6 °C using MATLAB and 1.9 C using Dragonfly. In Sant Martí, the average UHI intensity varies between 2 °C and 1.7 °C using MATLAB and Dragonfly, respectively. The average higher UHI intensity is due to higher daytime air temperatures estimated by MATLAB. Conversely, the nighttime UHI intensity calculated by the two versions is very similar.

Figure 3 compares the results for the *green* and *no-green* scenarios, indicating that the model exhibits poor sensitivity to vegetation changes in compact urban fabrics. It must be noted that the UWG-MATLAB version allows modelling trees and vegetated areas, while the Dragonfly version also models green roofs. However, the results do not show any significant difference in the ability to model the positive impact of vegetation on urban air temperature by any of the two versions.

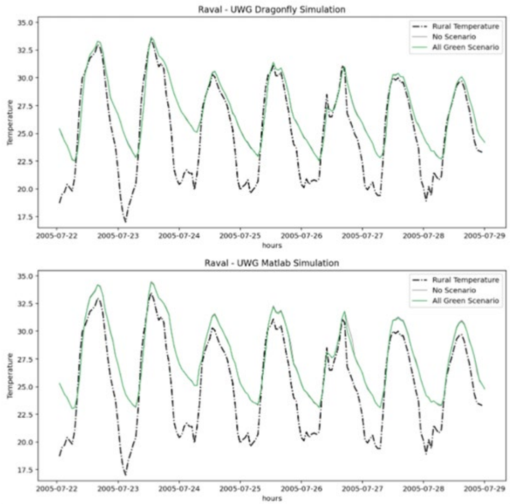

Figure 3
Raval case study comparison in ideal scenario: *all green* vs *no green*

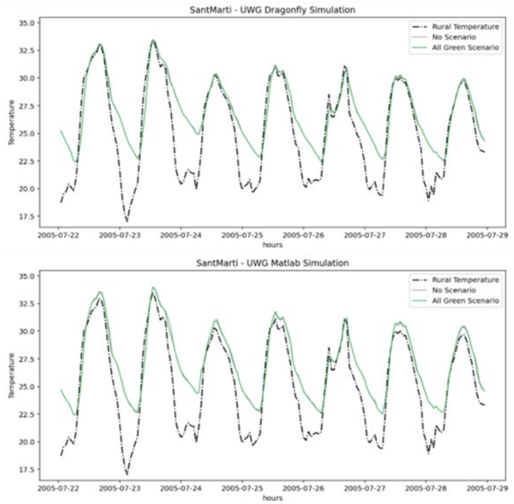

Figure 4
Sant Mart case study comparison in ideal scenario: *all green* vs *no green*

Figure 5 represents the hourly variation in the simulated canyon air temperature in the *all-green* compared to the *no-green* scenarios.

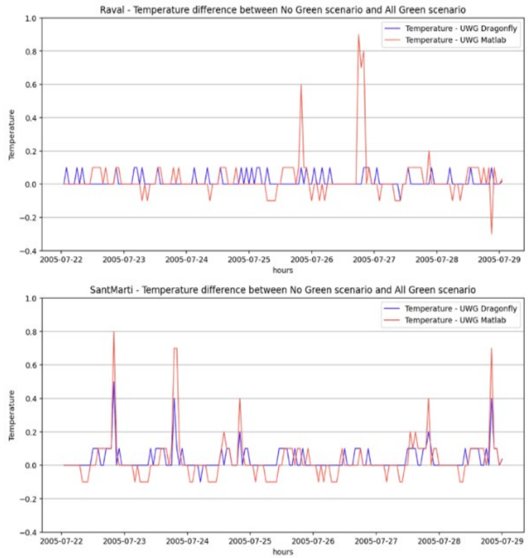

Figure 5
Hourly air temperature difference in ideal scenario: *all green* vs *no green*

The positive values represent reductions in temperature, reaching a maximum of 0.9 C, but only in specific hours of the day, around temperature peak and in some nighttime intervals.

The average reduction of urban air temperatures determined by increasing the vegetation to its maximum in the two scenarios is represented in Figure 5. In Raval, the *all-green* scenario is 0,02-0,03 C cooler than the *no-green* while in Sant Martí the temperature reduction reaches 0,03-0,04 C, as calculated by MATLAB and Python respectively.

The plots in Figure 5 also show that, even if moderate, the temperature reduction due to vegetation estimated by the MATLAB version is higher than the one estimated by Dragonfly. This is surprising because the Dragonfly simulations also accounted for green roofs in all the buildings of the urban area. To date, there is no accessible documentation regarding how green roofs have been implemented in Dragonfly. However, these results suggest a negligible effect on urban air temperature.

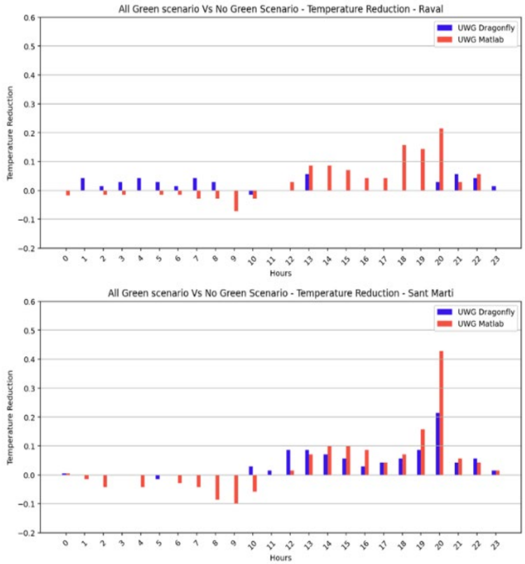

Figure 6
Average reduction of air temperature in the *all-green* scenario.

It would be important to further develop and test this Dragonfly component as it could lead to misleading results regarding the potential beneficial effects of green roofs and other nature-based solutions applied at the district scale. Alternative urban canopy models to UWG have improved the urban water balance calculation and the evapotranspiration modelling to account for the effect of green roofs and green facades on building energy demand and urban air temperatures (Moradi, Krayenhoff and Aliabadi, 2022; Afshari, 2023). However, these models still need advanced technical and theoretical knowledge to be run and cannot be easily integrated into the design workflow, especially by non-specialist users.

Figure 7 shows the hourly temperature reduction achieved with the *all-green* scenarios throughout the year as simulated by the Dragonfly UWG module for the two urban morphologies. Here we can see a general slightly positive effect in the afternoon during the summer months, reaching a maximum cooling of 1 °C but only at specific times of few days of the year.

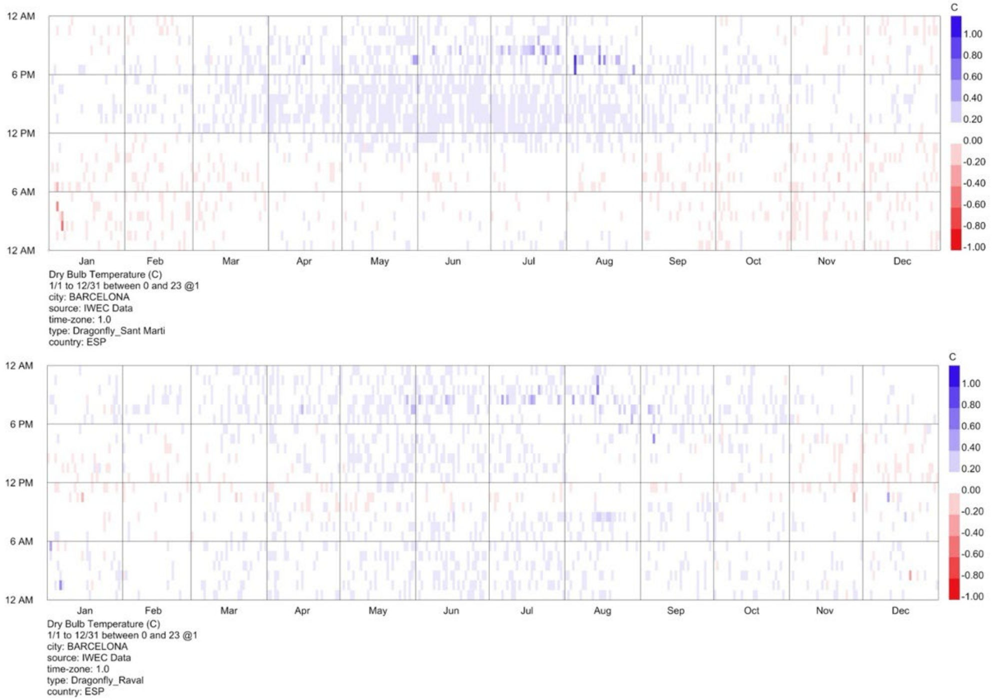

Figure 7
Hourly air temperature reduction in the *all-green* scenario (Dragonfly model)

Therefore, these figures confirm the reduced ability of the UWG model to account for the positive effect of urban vegetation on UHI mitigation. The very similar results for Raval and Sant Martí indicate that this is not due to urban compactness.

Existing studies reporting sensitivity analyses conducted on UWG have yielded varied results regarding the influence of vegetation parameters.

For instance, the increase in tree cover was found to have a significant impact on urban air temperature in Basel (Bueno et al., 2013) and Barcelona and Rome (Salvati et al., 2019), while it was found irrelevant in Abu Dhabi (Mao et al., 2017). In all studies, the vegetation parameters did not show great sensitivity compared to other input parameters (meteorological factors, urban and building characteristics). However, the contrasting results on the effect of vegetation can be also explained by the different versions of UWG. An important update was implemented on the humidity calculation in the current (V4) UWG Matlab-version compared to the first version V1. In UWG V1 there was a simplified water balance calculation, leading to modified absolute humidity values in the urban canyon depending on vegetation (Bueno et al. 2013). This has been omitted in the current Matlab-version, as it was not validated and not fully considered in the four UWG coupled-modules (Mao et al., 2017). This can explain the reduced contribution of increased tree cover to UHI mitigation, in both the compact - Raval - and less compact - Sant Martí - urban fabric.

In addition, it is worth mentioning that four additional issues of the UWG model may have contributed to the reduced ability to assess the mitigating effect of vegetation (Xu et al., 2022; Dardir and Berardi, 2021; Moradi et al., 2021; Moradi, Krayenhoff and Aliabadi, 2022).

First, a simplified binary representation of vegetation (presence or absence), resulting in abrupt transitions in albedo with seasonal changes.

Second, UWG failed to properly account for the effect of vegetation shading on the solar radiation received by the road surface, leading to counterintuitive results such as increased air temperature with increased vegetation coverage.

Third, an underestimation of the vegetation cooling effect stems from limitations in representing both shading and the evapotranspiration process.

Fourth, a limited consideration of warming effects by blocking thermal losses from urban surfaces. In order to improve this tool, the integration of evapotranspiration or dynamic vegetation models could be included. Recent studies try to overcome these limitations by proposing updated or extended versions of the original model capable of giving a more nuanced effect of vegetation, a more precise modelling of the urban characteristics and of the energy balance or including other important variables. However, to date, these versions are not available in any of the most widespread spatial modelling software, nor in the stand-alone Matlab version.

CONCLUSIONS

This paper compares sensitivity to urban vegetation parameters of the two most diffused versions of Urban Weather Generator: the stand-alone Matlab and the Phyton Dragonfly for Grasshopper.

The study wants to highlight actual limitations in the adoption of the UWG tool for design scenario purposes across diverse urban and climatic contexts. At the same time, it seeks to raise users' awareness in the interpretation of the simulation results and in the assessment of the effect of vegetation while trying to mitigate the urban heat island in the design process. While the UWG serves as a computationally efficient tool for urban microclimate simulation, its capacity to accurately model the nuanced effects of vegetation on UHI is subject to discussion.

Through sensitivity analyses for two typical urban fabrics in the Mediterranean climate, a reduced ability of the UWG model to account for the positive effect of urban vegetation on UHI mitigation has been demonstrated, in particular for the Dragonfly version.

It is pertinent to note that this version, as differentiated from its stand-alone counterpart, is integrated within the Grasshopper environment, thereby facilitating a comprehension of the interrelationships between the spatial and physical attributes of a tri-dimensional model and the performance in terms of the urban microclimate.

It is observable that an increasing number of designers, frequently characterised by limited and non-academic preparation in this specialised domain, are now resorting to the application of these simulation tools during the design process. While this circumstance is possessed of considerable potential for the more expansive dissemination of methodologies for the evaluation of the urban microclimate in urban planning and design, it simultaneously harbours the inherent risk of an inappropriate utilisation of the aforementioned tools and the resultant outputs. Such misapplication may eventuate in asymmetrical design outcomes, not aligned with the expected performance.

Consequently, it is becoming increasingly important for designers to have adequate knowledge and awareness of the physical phenomena that shape the urban microclimate. At the same time, it is essential that simulation tools provide reliable results—even before they are widely adopted in design practice. Given the pressing exigency to enhance thermal resilience within urban areas, the effects of vegetation can no longer be misinterpreted or disregarded.

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