Blue-Green infrastructure determines the microclimate mitigation potential targeted for urban cooling

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Abstract. Urban Heat Island (UHI) exacerbated by global warming can increase the thermal load in cities, which leads to more extreme climate events. One of the strategies to mitigate the impact of extreme climates and UHI is through nature-based solutions such as the Blue-Green Infrastructure as it provides environmental and community benefits. However, Blue-Green Infrastructure's role in urban cooling in the tropics still needs to be further investigated. Therefore, this study examined the role of Blue-Green Infrastructure on microclimate modifications in an urban park. Microclimate measurements were made using systematic random sampling with random start (total of 64 sampling points) at a waterbody (Blue Infrastructure) and tree and grass (Green Infrastructure) areas during solar noon time (1200-1400). Blue-Green Infrastructure showed greater microclimate benefits compared to the open space with the reduction of air temperature by up to 1.6°C. However, green infrastructure had greater cooling benefits compared to Blue Infrastructure especially trees with significantly lower air temperature and solar radiation interception (0.71°C and 250.3 W/m², respectively) as well as higher relative humidity (12.17%). Moreover, stand characteristics determine the microclimate mitigation function. This study provides a useful indication of the role of blue and green spaces in urban cooling, where it further emphasizes the importance of Blue-Green Infrastructure utilization in urban landscapes. It further recommends that urban planners, managers and policymakers should consider these strategies for urban cooling purposes: 1) Utilising Blue and Green Infrastructures especially trees 2) Tree canopy cover and DBH should be set as priority traits.

1. Introduction
Urbanization is the phenomenon of the changes in the urban growth patterns (i.e., settlement), economic, social and environmental processes [1, 2]. The shift from rural to urban environments is one of the main reasons that lead to urbanization and affect the urban ecological processes, thus influencing the urban residents in many ways. Currently, 55% of the global population is living in urban areas and the shift is projected to continue by 68% in 2050 [3]. With urbanization, the destruction and degradation of natural ecosystems are unavoidable. Many more developments will occur in cities changing the land cover from natural vegetation to artificial materials such as concrete and asphalt for the pavements, roads, buildings and other urban structures [4].
With urbanization, it causes fragmentation of the green areas within the urban areas and over time, these isolated fragments will become smaller [5]. Not only that, land cover changes and reduction of green areas alter the heat energy balance [6] and lead to changes in the urban climate [7,8]. Replacement of the vegetation to artificial materials added by the urban heat contributes to Urban Heat Island (UHI) [9]. In the context of UHI, the urban area has different climates than rural areas [10,11]. The urban climate is typically characterized by higher air and surface temperatures, with lower humidity and restricted atmospheric exchange [12].

Multiple strategies for adaptation and mitigation strategies can be implemented to reduce the impact of UHI on future urban cooling and human health and wellbeing. This includes the utilization of green and blue spaces, cool roofs and a combination of all as these land covers could affect the atmosphere and land surface temperature [13,14]. The Blue-Green Infrastructure is gaining interest globally as a nature-based solution for urban cooling [15]. It combines natural and designed landscapes in urban areas that embedded the blue and green spaces aiming to provide various environmental benefits, including urban cooling [16]. Green infrastructures refer to any form of vegetation, while blue infrastructures represent water bodies such as lakes and rivers. These infrastructures are not only for the combination and integration of green and blue elements in cities but also for policy intentions and social benefits from the ecosystem services they provide [17]. The benefits from Blue-Green Infrastructure could potentially lead to the sustainability and resilience of cities [18].

Through the use of Blue-Green Infrastructure, it mitigates the UHI by both elements providing a synergistic cooling effect in urban parks [19]. Through the enhancement of ecosystem services especially on urban cooling, the Blue-Green Infrastructure is often implemented in the planning strategy for UHI mitigation [20]. However, green and blue spaces may differentially affect the cooling effect of the environment [21]. The green infrastructure such as trees and grass could provide cooling benefits at micro and local levels thus affecting the thermal comfort of pedestrians [22,23]. On the other hand, the blue infrastructure provides benefits to the surrounding park area and also could reduce the heat stress of nearby built-up areas [24]. In addition, when streets are planted with different percentages of tree canopy cover, it could lead to different microclimate conditions and human thermal comfort [23]. Thus, it is also projected that when different elements of infrastructures such as the blue and green spaces are being implemented in the urban areas, they might provide different microclimate conditions. Moreover, with the wide implementation of Blue-Green Infrastructure as nature-based solutions, priorities should be set to conduct further research in determining the impacts of applying the Blue-Green Infrastructure especially for its ecosystem services, i.e., urban cooling and reducing the effects of extreme events, i.e. heatwave [25,26,27].

Therefore, the overarching aim of this study was to investigate the influence of Blue-Green Infrastructure on the microclimate condition in an urban park. Specifically, the objectives were:

a) To determine the microclimate benefits of Blue-Green Infrastructure in an urban park
b) To compare the influence of trees, grass and waterbody on the microclimate of urban parks
c) To determine the relationships of stand characteristics and microclimate regulation

This study will be beneficial in informing the cooling potential of the Blue-Green Infrastructure and provide further recommendations to the urban planners and managers for future urban management and planning.

2. Methodology

2.1. Description of study site

The study was conducted at the Putrajaya Botanical Garden, Precinct 1, Putrajaya, Malaysia (2.9448° N, 101.6955° E). Putrajaya is known as a City in the Garden and Putrajaya Botanical Garden covers over 92 hectares. The garden is divided into five sections, which are based on the types of plants and the topography of the area. The study area took place in multiple parts of the garden. Figure 1 shows the map of Botanical Garden, Putrajaya.
2.2. Experimental design

2.2.1. Characteristics of sample area. The study area was divided into four different sites within the park: trees, grass, waterbody and open (not shaded by trees and other infrastructures). Green infrastructure includes the trees and grass area while the water body has blue infrastructure. For grass and waterbody, a systematic random sampling with the random start was used where the first point was randomly selected and the following sampling point was systematically assigned with a distance of 10 meters apart. For the waterbody area, the sampling points were above the waterbody surface on the provided platform trail and trees and buildings nearby were avoided. Trees were sampled at different areas throughout the garden either in single or cluster planting design including *Pometia pinnata*, *Borassus flabellifer*, *Dyera costulata* and *Neobalanocarpus heimii*. For each site, 16 sampling points were selected, with a total of 64 sampling points. All the sampling points for trees, grass and open areas were positioned at least 30 meters away from any waterbody and any obstruction of nearby buildings.

2.2.2. Microclimate measurements. Four microclimate parameters were measured at each sampling point: air temperature (°C) and relative humidity (%), wind speed (m/s), and solar radiation (W/m²). Microclimate measurements were conducted at solar noon time (1200-1400) on sunny days, avoiding cloudy and rainy days. Wind speed and solar radiation were recorded five times at each point and averaged, while air temperature and relative humidity data were only measured once. All the microclimate data were measured at 1.1 meter above the ground level. The air temperature and relative humidity were measured using Heat Index Lutron WBGT-2010SD meter, wind speed using Skywatch Atmos Thermo-Hygro-Anemometer and solar radiation using Pyranometer MP-200. The microclimate measurements were carried out for four cycles from 28 September to 2 October 2020.

2.2.3. Stand characteristics measurement. Stand characteristics such as ground vegetation (%), canopy cover (%), tree height (m) and tree diameter at breast height (DBH) were recorded at each sampling point for the tree area. While for grass areas, only ground vegetation was measured. The canopy and ground cover were measured using Gap Light Analysis Mobile App (GLAMA) software, tree height using LaserAce 1000 Rangefinder Hypsometer and diameter tape for DBH.
2.3. Data analysis
All the data were analyzed using the IBM Statistical Package of Social Science (SPSS) version 26 software. For Blue-Green infrastructure microclimate benefits, it was calculated based on the microclimate difference between Blue-Green infrastructure with the open area and statistically tested using t-test analysis. For the comparison of the grass, tree, and waterbody areas, One-Way ANOVA was used and once significant (p≤0.05), further posthoc analysis using the Least Significant Difference was conducted. Moreover, linear regression was used to find the relationships between stand characteristics and microclimate conditions.

3. Results and discussion
3.1. Microclimate benefits of Blue-Green Infrastructure
The microclimatic benefits showed that all blue and green infrastructures significantly reduced the air temperature by up to 1.59°C (p≤0.001) (table 1). Relative humidity and solar radiation were variable amongst sites. It showed that the green infrastructure was up to 11.9% and 105.2 W/m² significantly greater relative humidity and lower solar radiation, respectively compared to the open areas (table 1). However, open areas had significantly lower wind speeds up to 0.7 m/s (p≤0.001) compared to the Blue-Green Infrastructure areas (table 1).

| AREA       | Blue-Green Infrastructures Benefits | Δ Air Temperature (°C) | Δ Relative Humidity (%) | Δ Wind Speed (m/s) | Δ Solar Radiation (W/m²) |
|------------|-------------------------------------|------------------------|-------------------------|-------------------|-------------------------|
|            | Average ± S.E. p-value              | Average ± S.E. p-value | Average ± S.E. p-value | Average ± S.E. p-value |
| Grass      | 1.59 ± 0.17 0.000                    | -2.791 ± 0.450.000    | -0.71 ± 0.12 0.000     | 47.82 ± 14.210.001 |
| Tree       | 1.56 ± 0.20 0.000                    | -11.86 ± 1.100.000    | -0.60 ± 0.13 0.001     | 105.20 ± 0.000      |
| Waterbody  | 0.88 ± 0.26 0.001                    | 0.31 ± 0.62 0.616     | -0.69 ± 0.13 0.000     | -145.10 ± 19.68     |

Note: The differences were calculated based on the difference of mean values in open and in Blue and Green Infrastructures areas. The negative value represents the Blue-Green Infrastructure having a greater mean value of the measured parameter.

The air temperature at Blue and Green Infrastructures was lower than the open area due to the ground surface structure at the open area. Due to the pavement materials and with no shading from buildings and trees, the pavement surface receives direct solar radiation [30,31]. This has led to greater heat exposure and storage on the pavement surface, which signifies the greater air temperature in this area [32,33].

On the other hand, the transpiration process from green infrastructures releases water vapour into the atmosphere affecting the relative humidity. It thus contributes to the cooling of the urban environment by lowering the air temperature [34]. Trees act as a wind barrier as the stand structure and canopy obstruct the wind movement thus reducing the wind speed at the tree area [35]. However, all the blue and green infrastructures did not lower the wind speed and in fact, had greater wind speed than the open area.

3.2. Microclimate condition of grass, tree and waterbody
The microclimatic conditions assessed at each of the Blue-Green Infrastructure areas showed that the grass and tree areas did not significantly differ in their air temperature however, both were significantly
different to the water body area (34.31°C and 34.33°C, respectively, at \( p=0.909 \)) (figure 2). Waterbody showed the greatest air temperature with 35.02°C compared to the green infrastructures (up to 0.71°C difference) \( (p\leq0.05) \). Thus, this reflects significantly lower relative humidity at the blue infrastructure area compared to the green infrastructure area with 49.05% (up to 12.17% difference) \( (p\leq0.001) \) (figure 2). Moreover, the tree area had significantly the greatest relative humidity (61.22%) compared to the grass area (52.15%) at \( p=0.000 \).

Similar to the air temperature results, solar radiation was significantly lowest at tree area (456.39 \( \text{W/m}^2 \)) followed by grass (513.76 \( \text{W/m}^2 \)) and waterbody (706.69 \( \text{W/m}^2 \)) (up to 250.3 \( \text{W/m}^2 \) difference). Interestingly, solar radiation in the grass and open areas was not significantly different, and the waterbody was significantly the highest even when compared with the open area \( (p\leq0.000) \) (figure 2). On the other hand, wind speed did not show any significant difference between all sites \( (p\geq0.05) \) (figure 2).

For stand characteristics, the tree area had the highest canopy coverage with 59%, while the grass area had the highest ground coverage with 60% (table 2). With the increase of vegetation coverage, it is expected that the microclimate will be influenced, and as reported in this study, the air temperature was reduced, thus will also affect land surface temperature [31]. Moreover, the transpiration processes mentioned in Section 3.1 and the shading from the tree canopy could block the solar radiation [30,36]. The tree provides radiative cooling benefits through shading by intercepting the solar radiation and reducing shortwave radiation from reaching the ground and surrounding environment [37].

On the other hand, the water body had no coverage from any trees and other infrastructure thus, it makes sense that this area had the highest air temperature than the green infrastructures. Interestingly, the relative humidity of the waterbody was lower than the vegetation area and this finding is similar to research by Thani et al. (2013) [38] comparing the vegetation stand area and waterbody. With lower relative humidity, it increases the air temperature and according to Du et al. (2016) [39], the moisture could be advected away by the wind. Moreover, the waterbody absorbs the surrounding heat and the direct heating from solar radiation increases the heat storage, hence increase its air temperature in the waterbody area [40].
Figure 2. The mean value of air temperature, relative humidity, wind speed and solar radiation at each of the Blue-Green Infrastructure areas of Grass, Tree, Waterbody and the open area. Different letters denote significant differences between areas.

3.3. Relationships between stand characteristics and microclimate
Table 2 presents the stand characteristics of ground cover, canopy cover, DBH and height. Ground cover for trees accounted for 16.3% while grass covered 60.3%. On the other hand, the tree canopy cover, DBH and height were 58.68%, 20.79% and 32.95%, respectively.

**Table 2.** The stand characteristics of trees and grass areas. The mean value and S.E for ground cover were measured at trees and grass areas while canopy cover, DBH and height were measured only at tree areas.

| Value | Stand Characteristic          | Ground Cover (%) | Canopy Cover (%) | DBH (cm) | Height (m) |
|-------|------------------------------|------------------|------------------|----------|------------|
|       | Total                        | Tree | Grass | Total | Tree | Grass | Total | Tree | Grass | Total |
| n     | 16                           | 16   | 16    | 32    | 16   | 16    | 16    | 16   | 16    | 16    |
| Mean  | 16.25                        | 60.27 | 38.26 | 58.68 | 20.79 | 32.95 |       |       |        |       |
| S.E.  | 3.33                         | 3.86  | 4.68  | 1.57  | 3.14  | 2.94  |       |       |        |       |

It is important to understand the effect of stand structure on ecosystem functions and processes and specifically, we wanted to know how it affects the microclimate condition. In the relationships between stand characteristics and microclimate conditions at green infrastructure area, the air temperature and solar radiation under the tree canopy were significantly decreased with increasing canopy cover (p≤0.05, figure 3). Similarly, solar radiation significantly decreased with increasing DBH (p≤0.05, figure 3). On the other hand, solar radiation and relative humidity as well as solar radiation and wind speed significantly increased with increasing ground cover percentage and height, respectively (p≤0.05, figure 3).

As observed in this current study, the increase of canopy cover and DBH lowers the air temperature. The greater the leaf area index and differences in the canopy cover could affect the air temperature [41,42]. Moreover, with the increase of canopy cover, the solar radiation would be lower as the tree canopy cover intercept the direct shortwave radiation and reduce the heating effect on the surrounding. Therefore, increasing both the canopy cover and DBH would further contribute greatly to urban cooling.

On the other hand, when ground cover increases, the relative humidity and solar radiation will increase. Again, this further justifies the importance of the humidifying effect from vegetation and through the increase in transpiration, it creates a humid condition above the surface and reduces the surface heating [43]. Moreover, the wind speed and solar radiation increase with height. With a higher tree canopy, the lower part of a tree is more exposed, hence allowing more solar radiation to penetrate the lower and surface areas. While for wind speed, it is known that tree height is the foremost morphological trait in determining tree wind speed condition [44]. Thus, trees with their canopy near to ground could lower the solar radiation and act as windbreaker.
Figure 3. Linear relationships between air temperature, relative humidity, wind speed and solar radiation and stand characteristics of canopy cover, ground cover, DBH and height. The value of ground cover was measured at trees and grass areas while canopy cover, DBH and height measured only at tree area.

4. Conclusion
These findings showed that the Blue-Green Infrastructure aids in urban cooling where the air temperature and solar radiation mitigation benefits were up to 1.6°C & 105 W/m², respectively,
compared to the open area. However, the blue infrastructure could provide different microclimate mitigation benefits. Green infrastructure such as trees and grass exhibited greater cooling potential compared to the waterbody. However, the tree was best in its contribution to urban cooling through its microclimate regulation functions by providing the greatest air temperature and solar radiation reduction (0.71°C and 250.3 W/m², respectively) as well as its potential in increasing the relative humidity (12.17%). This was then followed by grass and, lastly, the waterbody area. On the other hand, it is also important to note that stand characteristics determined the microclimate mitigation function where future urban planning and management should consider: 1) Tree canopy cover and DBH should be set as priority traits for urban cooling purpose, 2) the ground cover helps in increase relative humidity and 3) Tree with height closer to ground level could be beneficial in reducing the solar radiation and act as windbreaks.

Some recommendations could also be made from the findings of this study. The utilisation of trees in urban areas for urban cooling should be increased due to its microclimate benefits. Not to forget that grass areas should also be included as one of the microclimate mitigation strategies. Moreover, planting trees alongside the blue infrastructure such as the waterbody could help as the waterbody alone contributed to the greatest air temperature and lowest relative humidity compared to the green infrastructures. In addition, this combination of both tree and waterbody could increase the synergistic cooling effect to the urban environment. Lastly, stand characteristics are also important in future urban tree planting planning.

It is hopeful that this study could provide useful information on the role of blue and green infrastructures targeted for urban cooling. The urban managers, planners and policymakers should optimize the benefits of green-blue infrastructure in cities, where some significant blue and green elements should be marked in future planning by integrating the understanding of their role in microclimate mitigation i.e. urban trees. Moreover, in future tree species selection, important characteristics of the green infrastructures i.e. tree canopy cover and DBH aiming to optimize the urban cooling benefit should also be highlighted.

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