International Journal of Education and Social Development
ISSN: 3078-9931 (Print), ISSN: 3078-2287 (Online) | Vol. 8, No. 2, 2026

Exploration of Urban Shade Accessibility and Improvement Paths for Outdoor Thermal Comfort from the Perspective of Blue-Green Infrastructure

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Abstract: How to Increase Shade Availability and Improve the Outdoor Thermal Environment of Cities with Blue-Green Infrastructure. Rather than providing new empirical data, it collects existing research on green and blue infrastructure, urban microclimates and thermal comfort indices to propose a path for integrating vegetation and water in heat-resilient public spaces. First, in this discussion, the concept of urban resilience and heat reduction provided by blue-green infrastructure through shading, evapotranspiration and modification of surface energy balance will be introduced; then, it will be explored how trees, ground cover and water bodies specifically alter radiant and air temperatures in streets, parks and waterfronts. According to biometeorological studies using indices such as physiological equivalent temperature (PET) and the Universal Thermal Climate Index (UTCI), this paper introduces design variables that affect the perception of thermal comfort, including sky view factor, canopy cover, configuration and accessibility. Shade accessibility should be considered a problem of spatial inequality in the planning of blue-green infrastructure, and all people need to be able to reach a cool microclimate during a heatwave. Finally, the paper proposes some practical rules for combining shade, ventilation and moisture in urban design, and does not make excessive claims about cooling performance beyond what has been reported in the cited literature.

Keywords: Blue-green infrastructure; urban shade accessibility; outdoor thermal comfort; urban microclimate; PET; UTCI.

1. Introduction

Urbanisation and climate change have increased the heat stress in many cities, and now outdoor thermal comfort is a problem for public health and life quality. Heat waves and high background temperatures are intensified by dense built-up areas, a lack of trees, and many impermeable surfaces; thus, the urban heat island effect is more severe for vulnerable groups.

Blue-green infrastructure has been put forward as a way to reduce the heat island effect in cities and enhance resilience by combining plants and water bodies. Trees, parks, wetlands and blue corridors can reduce the temperature in a specific area by shading, evapotranspiration and other means to make it more suitable for people to live and work outdoors.

This paper provides a conceptual exploration of urban shade accessibility and improved outdoor thermal comfort paths through the lens of blue-green infrastructure. It does not present new empirical data but rather synthesizes existing research to connect evidence on microclimate regulation, thermal indices and spatial equity in an integrated way for planning and evaluating shade and cooling in cities.

2. Blue-Green Infrastructure and Urban Heat Resilience

Green infrastructure is a system of natural and semi-natural areas that are planned and managed to provide ecosystem services, such as climate regulation and heat reduction [1-2]. Blue infrastructure, such as rivers, ponds and wetlands, can be used with blue-green systems to provide multiple cooling effects through shading, evapotranspiration and thermal buffering [3][4]. Reviews of urban heat mitigation strategies indicate that vegetation and water surfaces are highly effective at lowering near-surface air temperatures and surface temperatures in densely built-up areas [2][3].

Staddon and others have connected green infrastructure with urban resilience, and multifunctional green networks can support biodiversity, stormwater management and social benefits simultaneously, as well as cooling [1]. Gunawardena and others have compiled evidence on green and blue infrastructure for reducing the intensity of the heat island effect; trees, parks, water bodies and green roofs can lower surrounding temperatures by several degrees under certain conditions [3]. Models for Vienna show that targeted increases in vegetation and open water, along with reductions in the density of buildings and pavements, can significantly lower the urban heat load [4].

Based on the above results, blue-green infrastructure should be planned at all levels, from single-street trees to district-level corridors, to create redundant and connected cool spaces. However, the actual effect of such measures varies depending on the configuration, scale and environment; they are not guaranteed to be uniformly cool everywhere [1][3][4].

3. Urban Trees, Shade and Microclimate Regulation

Urban trees are one of the subjects of research on green infrastructure for heat reduction and thermal comfort. Systematic reviews and comparative studies have shown that tree canopies can reduce thermal exposure and surface temperature, but the degree of cooling varies from place to place [2, 5]. Rahman and his colleagues have compared the cooling effects of five representative urban tree species, and these differences are related to their growth and physiological characteristics [5].

Microclimate studies have found that trees are relatively cool because of shade. Trees block sunlight, lower the average radiant temperature and short-wave radiation reaching people

and objects, thus reducing the feeling of heat stress [10-11]. Field observations of shaded and sunny areas in street canyons and open spaces consistently show a lower mean radiant temperature and improved thermal comfort under tree shade, even when the reduction in air temperature is relatively small [6, 10].

Different kinds of trees have different effects of shade, and so do their crowns, canopies and spaces. Research on sky view factor shows that a small sky view can be achieved by a large crown and suitable spacing, thereby reducing radiant exposure and improving the environment in street canyons [10-11]. Based on the above results, urban shade planning should focus on canopy structures that optimise both shading and airflow rather than adding more trees [5][10].

4. Blue-Green Configurations and Cooling Paths

Green and Blue can be used together to increase the cooling effect through a combined mechanism. Model construction for Vienna and other cities has shown that vegetation and open-water surfaces can reduce the urban heat load together, and this effect is strongest in densely built-up areas where additional evapotranspiration and shading significantly alter the surface energy balance [3,4]. Blue infrastructure, such as ponds, rivers and wetlands, cools the surrounding area by evaporation and thermal storage; green infrastructure provides shade and latent heat flux [3,4].

Systematic reviews of blue-green infrastructure in temperate climates have identified the necessary parameters for heat reduction, such as the extent and arrangement of water bodies, the leaf area index of street trees, the hydration level of green roofs, and the direction of green walls [2-3]. Shade, moisture and surface reflectivity at different times of the day and in various urban areas all affect cooling.

Recently, research on the configuration-sensitive assessment of blue-green spaces in large cities has shown that cooling benefits are related to the patch size, connectivity and structural dominance over impervious surfaces [3]. Small, isolated patches can provide local cooling but do not offer extensive cooling; large, connected corridors can fragment heat accumulation areas and extend the range of cooling. Based on the above analysis, the design of the improvement path for thermal comfort should be continuous blue-green networks rather than isolated decorative elements [1][3][4].

5. Thermal Comfort Indices and Assessment Frameworks

Outdoor thermal comfort is generally shown by combining several meteorological factors into a single index of perceived heat stress. Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) are frequently used as reference values to assess the thermal environment of cities [7-9]. PET and UTCI are combinations of air temperature, humidity, wind speed and mean radiant temperature that reflect a person's heat balance.

Höppe introduced PET and, later on, used it in urban studies to provide a neutral range and stress category for design-relevant targets in outdoor spaces [8]. Blazejczyk and others have compared UTCI with other indices, shown that it is more sensitive to radiation and wind, and proposed thresholds for moderate, strong and extreme heat stress [9]. The above tools can be used to assess the change in temperature under blue-green infrastructure interventions compared with comfort standards.

RayMan is a model that can determine the mean radiant temperature and thermal index of simple and complex urban areas by considering sky view factor, building surfaces and vegetation in radiation calculations [7]. Apply the above assessment systems to shaded and non-shaded environments to quantify the cooling effect of tree canopies, pergolas and water features on temperature, even in the absence of field data. The above indices are considered to be established tools in this conceptual paper and are not new measurements.

6. Shade Accessibility as a Spatial Equity Issue

Shade accessibility is the extent to which different groups of people can access a cool microclimate in hot weather. Although blue-green infrastructure can create thermally comfortable areas, it is not always evenly distributed in the city. Research on urban resilience and environmental justice shows that low-income and marginalized communities often have less tree canopy cover, fewer parks, and are further away from blue-green corridors [1][2].

Shade should be viewed as a basic environmental need rather than a convenience in terms of spatial equity. To enhance the accessibility of shade, map existing canopy cover, parks and waterfronts, identify access gaps, and prioritise interventions in heat-vulnerable areas. Add walking distance, public transport access and barrier-free routes to the shade planning to help more people enjoy the benefits of blue-green infrastructure.

A Design Strategy that only considers the city's overall average canopy cover or park area risk will fail to account for local differences in shade availability. GIS and thermal comfort indices can be employed for spatial analysis of areas that require more shade, and the effect of blue-green elements in reducing heat stress can be determined. Policy systems that link the construction of blue-green infrastructure to heat-health action plans and social vulnerability indices will provide more equitable access to shade.

7. Design Variables: Sky View Factor, Canopy and Ventilation

Design of outdoor thermal comfort should consider the causes of radiation, airflow and moisture. Sky view factor (SVF) is a measure of the proportion of the sky dome visible from a certain location, and it affects short-wave and long-wave radiant fluxes [10]. Adding trees or architectural overhangs to reduce the street canyon SVF generally lowers both the mean radiant temperature and perceived heat stress; however, excessive enclosure may restrict ventilation and lead to a heat island effect [10-11].

Based on empirical research and model construction, shading and ventilation can be combined to form a cool space. The canopy cover should be relatively shady and well-ventilated; a suitable proportion varies according to the local geometry, climate and tree characteristics [5, 10]. Multi-storey planting of trees, shrubs and ground cover can increase evaporation and lower surface temperature; however, it should be done so that it does not obstruct the wind.

Ventilation Paths include aligned street orientations and cross-ventilation in open spaces to reduce shading and moisture accumulation in blue-green infrastructure. Research on hot-humid microclimates has shown that, due to the urban structure and prevailing winds, heat stress may be

exacerbated or reduced [6]. Consider SVF, canopy structure and airflow in the Design rules to ensure that shade facilities are comfortable and do not increase the heat load of poorly ventilated areas.

8. Improvement Paths for Outdoor Thermal Comfort

All links in the chain for improving outdoor thermal comfort under a blue-green infrastructure system need to be strengthened. Add shade trees, pergolas with climbers and water features near the main pedestrian paths at the site level to create a microclimate with a lower PET and UTCI value in the peak heat. Select tree species with large crowns, suitable heights and favourable phenology to maximise shading and reduce interference with infrastructure [5-11].

At the neighbourhood level, construct connected green corridors and blue-green belts to reduce the heat island effect and offer people continuous shaded paths for daily life. According to the model, combining reductions in building and pavement density with increases in vegetation and water surfaces will achieve greater cooling effects than these measures alone [3-4]. Permeability, Albedo and Canopy Distribution are urban design parameters that can be optimised to form a more heat-resistant pattern of streets and open spaces.

The city's new plan for blue-green networks will ensure long-term heat resistance by building redundant and multifunctional systems. Policies to protect and expand the tree canopy, prevent the loss of small parks, and introduce water-sensitive urban design in development projects can enhance cooling functions over time. The optimisation path should also monitor and adjust iteratively based on thermal indices and user feedback, as the sense of comfort varies among different people and cultures.

At all levels, one should not overstate the cooling effect or believe that blue-green infrastructure alone can solve all heat-related problems. Shade and cooling measures should be combined with building-energy-efficiency measures, behavioural modifications and heat-health alert systems instead.

9. Limits of This Study and Future Directions

Based on previous studies of blue-green infrastructure, microclimate and biometeorology, this paper has proposed a concept for urban shade accessibility and improved outdoor thermal comfort. It does not offer new empirical data, simulations or case studies, and its conclusions are only general ideas supported by the cited literature.

In the future, more field data, thermal indices and spatial analysis will be added to the current system to map shade accessibility and comfort in various cities. Compare the results of various climate, urban-shape and socio-economic environments to optimise the design rules and fairness considerations for blue-green infrastructure.

In addition, based on the user-centric mode, research and participatory mapping can be used to collect data on people's perceptions and uses of shaded Areas to gain an in-depth understanding. Such work will help promote more responsive and inclusive planning for urban heat resilience.

10. Summary

Blue-green infrastructure is designed to provide shade and improve the thermal comfort of people in urban areas through the arrangement of trees, shrubs, water bodies, etc. Trees, parks and water bodies can reduce heat through shading and evapotranspiration; however, their effectiveness depends on the scale, connectivity and design parameters of sky view factor and canopy structure.

Based on the synthesis of previous research on green and blue infrastructure, microclimate regulation and thermal comfort indices have been established as planning and assessment criteria for shade and cooling interventions without new empirical data. Shade accessibility should be treated as a problem of spatial inequality, and the path for improvement should consider both technical performance and the social distribution of benefits.

In the future, empirical research will be conducted to explore various configurations and policies; at the same time, practitioners can apply the principles of shade, ventilation and moisture in urban design. Finally, effective blue-green infrastructure for heat resilience needs to be carefully and contextually combined with natural and built elements that support comfortable and inclusive outdoor spaces.

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