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Mitigating Public Health Impacts of Climate Change-Induced Extreme Heat Events with Strategic Urban Greening

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Abstract
The likely future increase and intensification of climate change-influenced extreme heat events poses a significant public health threat, particularly to those populations most vulnerable. Urban populations, which globally are the fastest growing, are exposed to additional heat stress during such events due to the urban heat island (UHI) phenomenon. Urban green infrastructure (UGI) is a network of green spaces, street trees and other urban vegetation including wetlands, rain gardens, green walls and roofs. Strategic implementation of UGI is advocated within urban planning and climate change adaptation literature as an effective and versatile strategy for heat mitigation in urban areas and supported by a growing empirical evidence base. The relationship between UGI and morbidity and mortality associations during extreme heat events has demonstrated some significant outcomes in recent research to further support UGI. For example, recent studies find increasing a city's vegetation coverage can lead to significant reduction in average seasonal summer temperatures (0.5 to 2°C) together with 5–28 % reduction in heat-related mortality rate. Similarly, urban heat-related morbidity has been related to both tree canopy cover and hard surface cover, and can be reduced significantly when tree canopy cover increases beyond 5% or hard surfaces decrease below 75%. Barriers to widespread adoption of UGI are not technical, but more related to an incomplete understanding of current and future climate impacts, and a lack of political acceptance of the climatic disruption societies face.

Keywords
Climate Change — Urban Greening — Urban Heat Island — Urban Green Infrastructure — Heat Stress.

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Contents

Introduction

The likely increase and intensification of climate change (CC) related heat waves or extreme heat events (EHE) poses a significant threat to public health, particularly those most physically or socially vulnerable [1–4]. As morbidity and mortality data from some significant EHE around the world during the last 20 years has shown, the impact of CC-related extreme heat on public health can be devastating [2, 5, 6]. Urban populations globally are the fastest growing, with cities already containing over half of the world's population [7]. Those living in cities are exposed to increased heat stress during EHE due to the UHI phenomenon [8, 9]. Robust climate projections reiterate the importance of ensuring appropriate and timely adaptation measures are being prioritised; increasing the resilience of a population is essential if vulnerability to future EHE impacts is to be decreased [10, 11]. Building both social and environmental resilience to the impacts of climate change on the ground is reliant on the actions of local governments and other public organisations in developing and implementing effective policies and planning strategies [12–14]. Strategic implementation of urban green infrastructure (UGI) is advocated within urban planning and climate change adaption (CCA) literature as an effective and versatile strategy for heat mitigation in urban areas [15–18].

There is a large body of foundational and emerging empirical evidence to suggest that an increase in vegetated area can reduce ambient air temperature in urban areas [16–21]. This concept is grounded in the scientific evaluation of thermal properties of plant biology [16, 17, 22, 23]. The relationship between green spaces and morbidity and mortality associations during EHE has demonstrated some significant outcomes in recent research [24, 25], although population demographics and dwelling characteristics can also be important factors in determining rates of mortality [26]. These findings further support UGI as a multi-functional option for adapting urban centres to extreme heat related climate change impacts [24, 25].

1. Climate Change and the Incidence of Heat Waves

According to IPCC's Fifth Assessment Report, heat waves are defined as events exceeding specified temperature thresholds over some minimum number of days, although no universally accepted definition exists [27]. Changes and projected future increases in heat wave frequency and intensity in many regions have been attributed to increased greenhouse gas (GHG) concentrations and their effect on climate, favouring warmer conditions [28–30]. Under a business-as-usual scenario of GHG emissions, Meehl and Tebaldi [31] project a large increase in EHE over the United States (US) and Europe. Recent work suggests that this may be tempered to some extent by the cooling effect of anthropogenic aerosol emissions, assuming they continue to be co-emitted with GHG emissions [32].

Since the mid 20^{th} century, increases in warm spell and heatwave frequency, intensity and duration have occurred [33]. Underscoring the importance of the 2015 Paris agreement to limit warming to 1.5°C, Perkins-Kirkpatrick and Gibson [34] report that increases in heatwave frequency between 4–34 extra days per season per degree of global warming, and highlight the potential for disastrous consequences associated with regional heatwaves if global mean warming is not limited to 2 degrees. These findings are corroborated by Mora et al. [35] who find that by 2100, the percentage of the population exposed to lethal EHE is projected to increase to 48% under a scenario with drastic reductions of greenhouse gas emissions, and 74% under a scenario of growing emissions.

Projected increases in heatwaves are dependent on the assumed GHG emissions scenario, with the largest increases anticipated under the RCP8.5 'business as usual' scenario [36]. However, heat waves are expected to be on the rise until 2040, even under the RCP4.5 emissions scenario (which assumes stringent GHG mitigation measures). Climate models project that the frequency of warm days and nights is likely to increase, while cold days and cold nights are likely to decrease.

2. Impacts on Cities

The IPCC 5^{th} Assessment Report notes there have been few attempts to quantify potential changes in future human exposure and vulnerability to extreme heat [37]. However, it is now understood that exposure to extreme heat depends not only on changing climate, but also on changes in the size and spatial distribution of the human population [38]. Due to the relatively coarse spatial resolution of global climate models, the impact of climate change at the scale of cities has only recently been explored. Importantly for human health impacts, Wouters et al. [39] find that the heat stress increase by the mid-21^{st} century will be twice as large in cities compared to their surrounding rural areas.

The exacerbation is driven by the UHI itself, its concurrence with heat waves, and rapid urban expansion, which transforms the landscape, affecting ecosystems [40] and land surface temperatures [41]. The issue of urban expansion is particularly critical in the developing world, where by 2050 two-thirds of their inhabitants are likely to live in urban areas [42]. In high economic growth countries such as China, projected regional temperature increases due to urban expansion may be as high as 5°C [43]. In a similar vein, Jones et al. [38] find that US population exposure to EHE increases from 4 to 6-fold in the latter half of the 21st century compared with levels in the late 20^{th} century, and that changes in population are as important as changes in climate in driving this outcome.

3. Vulnerability Of Urban Populations

Urban centres, in general, experience greater sensible atmospheric and radiative heat compared to their less developed rural counterparts [44]. Recognised globally, the UHI phenomenon has a very well supported empirical research history spanning over 30 years [44–47]. Cities contain more impervious heat absorbing materials like concrete, asphalt, and metals per unit area, compared to rural areas which contain more vegetation and permeable surfaces [23, 44]. Vehicles, air conditioning and other mechanical exhausts increase heat energy in urban areas [8, 48], while factors like the dense arrangement of tall buildings along streets can trap and reflect heat [23, 49].

Within urban areas there can be localised 'hot spots' where neighbourhood and even street scale differences in the intensity of the UHI effect are quantifiable [50]. Trapped heat reduces the rate of nocturnal atmospheric cooling [49, 50], which is shown to be a critical factor in heat stress recovery during EHE [2, 51]. This energy flux of urban areas is highly sensitive to micro-climate interruptions and is exacerbated during EHE [44, 50]. This means urban populations are further exposed to the intensified UHI sensation during EHE, increasing their vulnerability to heat stress related morbidity and mortality [4, 48]. However, heat vulnerability of urban populations is not distributed evenly across groups [52, 53] and land use attributes that affect individuals and communities as a whole [9, 52, 53].

The elderly, children, the economically disadvantaged, and immune-compromised individuals are among those most vulnerable to the impacts of extreme heat [9, 31, 44, 52, 54, 55]. Significant health vulnerabilities within cultural minority groups have also been highlighted in recent Australian and American based studies [1, 13, 56]. For example, an increase in adverse outcomes during EHE was reported to be correlated with a decrease in English comprehension [1, 56]. Owing to the effects of biological aging, increased likelihood of poor health condition and economic limitation, physical mobility issues, and higher social isolation, the elderly are considered most vulnerable during EHE [2, 52, 57]. These compounding factors decrease the elderly's ability to cope with extreme heat, and increase susceptibility to exposure and adverse physiological impacts [2, 52].

4. Urban Greening as an Adaptation Strategy

The concept of urban green infrastructure (UGI) is not new; street trees, public open spaces and gardens have been a central concept in the classic American 'City Beautiful' and the United Kingdom 'Garden City' models of historical urban planning [58]. More recently, the literature related to UGI refers to a holistic approach to landscape planning that draws on multidisciplinary concepts from fields such as ecology, urban planning and landscape architecture, engineering and public health [59–61]. Increasingly, UGI embodies the principles of the sustainability discourse via its consolidation of ecosystem, social and physical services [59]. Green open spaces, tree canopy cover (street trees), green roofs (i.e. gardens) and vertical greenery systems (i.e. facades/wall gardens), are the predominate landscape elements considered to encompass the modern interpretation of UGI [59, 62].

There is a large body of empirical evidence that suggests an increase in urban green space can directly reduce ambient air temperature in cities [17, 20, 21, 60, 63]. The evidence supporting the cooling properties of UGI are based on the physical properties of plant biology, namely evapotranspiration, increased albedo and shading opportunities [23]. The physical characteristics of the plants, their vertical structure, extent of cover and species composition have all been shown to influence cooling potential [16, 17, 22, 23, 64]. Vertical gardens or 'green facades' on walls of buildings in Melbourne (Australia) were shown to reduce daytime adjacent surface air temperature by up to 3.1°C and temperatures behind the plants on the wall surface were up to 9°C cooler [22]. In a study of vegetation cover extent and types during heatwave events in an arid and coastal region in California, Shifflet et al. [16] found that vegetation cover provided a significant negative feedback system with cooling of day time surface temperatures and night time air temperatures regardless of the climate type. For example, for every increase in vegetation cover there is a direct reduction in the measured temperatures. Taller continuous tree canopy and clustering of vegetation had a greater impact of cooling both times of day at the micro scale compared to bare ground (up to 6°C within 0.1m of the canopy and 3°C within 2m of the canopy), however the extent of unfragmented cover itself was more significant than tree height in cooling at the larger 'regional' scale of urban environments [16]. In contrast, Rahman et al. [65] suggest that single tree canopy (spaced non-continuous canopy cover) provides better a cooling effect for urban microclimate settings as it enables more evapotranspiration.

Variation of temporally and spatially reported differences in temperature among the different study types suggest localised characteristics (i.e. street canyon geomorphology), present complexities for implementation at a local scale.

Conclusion

Climate change is set to significantly impact cities and those who live and work within them. Robust evidence supports a future where the global population will experience extremes in meteorological events, including heat, with greater intensity and frequency because of CC [66]. The public health implications of these projections are profound. In many countries heatwaves have a greater impact on population health than any other natural hazard, and are associated with significant increase in mortality and morbidity rates [54].

The grave public health risks during EHE suggest increasing community resilience to extreme heat is essential for effective climate change adaptation [67–69]. The existing evidence in support of the microclimate cooling benefits of UGI is significant and growing, providing opportunities for extrapolation of data for application to specific localised climate conditions. Nevertheless, this is recognised as a complex, multidisciplinary area of practice [59, 61, 62]. Gaps in specific technical knowledge for implementation, maintenance and monitoring of UGI would benefit from further practical trials [63]. Refinement of studies assessing the microclimate altering properties provided by various green infrastructure typologies would be advantageous to implementing targeted site specific EHE mitigation. The relationships between UGI and morbidity and mortality associated with heat stress, as well as the relationship to other illnesses which impact the overall resilience of the community to heat stress, is becoming increasingly clear [24, 70, 71]. However, broader statistical analyses of hospital admissions during EHE and other relevant demographic data is needed to further strengthen evidence of significant relationships supporting the beneficial impacts of UGI on public health [72].

It is prudent to note that vegetation alone cannot completely resolve the challenges of EHE in all urban settings [73]. However, as the intensity and frequency of EHE increase, so will the requirement for increased resilience and flexibility of urban climate adaptation tactics [74]. As noted by Lin et al. [75] the are many challenges to the optimal implementation of UGI, inter alia, community perceptions of UGI; economic costs and benefits and the ease of new policy implementation. Therefore, a combined approach of mitigating options in addition to UGI requires urgent consideration in any judicious urban planning strategy [73].

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