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The Impact of Blue-Green Infrastructure on Morbidity and Mortality during Extreme Heat

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ABSTRACT

Background

Extreme heat events are one of the deadliest effects of our changing climate. Blue-green infrastructure aids with ambient temperature regulation and has an overall positive effect on human health. Studies documenting the impact of blue-green infrastructure on human health during extreme heat are fragmented across multiple disciplines, with no current synthesis completed.

Objective

To examine the current evidence regarding the impact of blue-green infrastructures on human morbidity and mortality during extreme heat.

Methodology

A PubMed literature review search was conducted in June 2024 using 13 common terms to describe blue-green infrastructure, five terms for extreme heat, plus health. Included studies evaluated a blue-green infrastructure variable and health outcome during measured extreme heat. Non-in situ human research was excluded. Synthesization was conducted using an ecosystems service theoretical framework.

Results

The PubMed search terms yielded 145 articles, 124 did not meet the necessary criteria, and 21 were synthesized. Sixty-seven percent showed a statistically significant (p-values 0.001 to 0.05) direct association between blue-green infrastructure presence and health outcomes during extreme heat. Mortality rate and mental health were studied most frequently. An additional 19% of studies found similar statistically nonsignificant trends. Three studies found no consistent interaction

Conclusion

Blue-green infrastructure may play a critical protective role for human health during extreme heat.

Public health implications

Blue-green infrastructure is an economically accessible and sustainable method of mitigating many of the effects of climate change, including water management and lowered surface temperatures. While its impact on health is likely multifactorial, its protective role on morbidity and other health outcomes during heat waves should be embraced as a viable part of future public health climate resiliency plans.

Keywords: blue-green infrastructure, morbidity, mortality, heat, resiliency

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INTRODUCTION

Extreme heat morbidity and mortality

Global temperatures continue to rise, and high temperatures are becoming increasingly common[1] and deadly.[2] The increasing frequency and intensity of extreme temperatures, driven by climate change,[1,3] pose significant challenges to global health.[2,4,5] Extreme heat increases mortality and morbidity across ecosystems.[6,7] Urban areas, characterized by high population densities and extensive impervious surfaces, are particularly vulnerable to extreme heat events.[3,8] The United Nations Secretary-General released a special statement on July 25, 2024, marking the previous week as the hottest ever recorded, reaching over 50 degrees Celsius across the globe. The statement highlighted 1300 who died on pilgrimage during Hajj, 120 million people across the United States under heat advisories, and a projected $2.4 trillion cost to global economies due to heat by 2030. Over 500,000 people are predicted to die this year of heat-related causes.[46] On the same day, the International Labour Organization reported that 2.4 billion people are currently at high risk of extreme heat, with 93% of workers in Africa, 83% in the Arab states and Asia, and 75% of the Pacific workforce directly affected.[47] The United Nations announced a four-part Global Call to Action to attempt to turn the tide. Part three challenges us to advance the resilience of economies and societies using data and science.[5,46] This review directly contributes to this United Nations imperative. Urban heat islands are pockets of built land whose surfaces repeatedly reflect and amplify solar energy, heating surfaces that later release the stored heat at night, elevating nighttime temperatures.[9] Anthropogenic heat refers to the temperature increase caused by human activity, including running air conditioners. The two create a self-feeding cycle of increasing localized temperatures. When combined with sustained high heat days, urban heat island temperatures can climb to 80% hotter than non-high heat days.[8] Heat waves are heterogeneously defined in the literature[10] with each study declaring the specific cutoffs used. The World Meteorological Organization defines it as a period of unusually hot days and nights for a location.[11] While several weeks of acclimation can allow healthy humans to tolerate higher temperatures, a heat wave occurs too quickly for biological adaptations beyond increased heart rate and sweating. When the body's preliminary adaptations fail, core body temperature rises, creating potentially deadly physical stress.[7] High ambient temperature intensity and duration increase mortality risk for a region.[10] This is particularly true for cardiac[12] and respiratory-related[13] morbidity and mortality. As we experience record levels of heat, our understanding of the extent of its health impact expands. Between March and May of 2024, at least 60 people died when daytime temperatures across India remained over 50 degrees Celsius for a total of 24 days.[14] Thirty-three deaths were attributed to the heat wave in one day alone.[15] In June 2024, Egypt reported 530 people dead while participating in the six-day Hajj Pilgrimage to Mecca in over 51 degrees Celsius temperatures.[16] Saudi Arabia put the death toll at over 1300.[17] The cause of death in heat-related events is often primary dehydration, heat stroke, or cardiovascular collapse. The heat event serves as the catalyst that exacerbates underlying illness or age and socioeconomically related vulnerabilities, making cause and effect less directly linked, but no less deadly. The United Nations notes, "the negative health impacts of heat are predictable and largely preventable." [51] Extreme heat's health effects are not equally distributed. Socioeconomic elements such as preexisting co-morbidities, social isolation, minority status, economic disadvantage, lower education, and extremes of age are strongly linked to increased health risks during extreme heat.[7,18] Reduced access to health care, drought, and food shortages amplify the health risks in the global south and areas with weak infrastructure.[2] The cost of rising temperatures to non-human ecosystems remains a complex and heartbreaking topic. Phenological shifts are already occurring and are expected to result in elevated non-random extinction rates and rising disease-carrying pest density.[6] Addressing global climate change-induced, heat-related health risks requires accessible and sustainable strategies. One potential option is blue-green infrastructure.[19]

Blue-green infrastructure's cooling effect

Blue-green infrastructure encompasses natural and semi-natural elements, such as parks, green roofs, vertical gardens, fountains, rivers, and lakes. Integrating water and vegetation into our built spaces increases resiliency through ecologic services such as temperature regulation, air purification, and flood mitigation.[19–22] These infrastructures can significantly reduce urban heat island effects by disrupting solar energy reflection and lowering temperatures via evapotranspiration (water evaporation from soil and the surface of plants) and solar radiation absorption.[21,22] While estimations vary by the type and size of blue-green infrastructure, daytime cooling of seven degrees Celsius during the day and nine degrees at night have been documented, and computer simulations estimated that for each 5% increase in tree density, temperatures lower by a full degree Celsius.[20]Urban greening is a dual-purpose strategy because it is both mitigation and adaptation. Trees, for example, reduce CO_2 through photosynthesis, protect against soil erosion, decrease air pollution, and lower ambient temperatures.[4] Green spaces have been linked to improved mental and physical health, reduced stress levels, and enhanced overall quality of life.[23] Building patterns throughout history inequitably distributed access to blue and green spaces.[23] The United States' decades-long use of redlining exacerbated these differences.Significantly lower vegetation levels in racially diverse neighborhoods compared to traditionally white areas were found across 102 American urban areas. Seventy years later, the average density of green vegetation still steadily decreased with the 1940 Home Owners' Loan Corporation score.[24]

Health impact of blue-green infrastructure during extreme heat

Despite blue-green infrastructure's ability to decrease local ambient temperatures[19–23] and the detrimental effect of high temperatures on health outcomes,[7,10,12,13] current literature demonstrating a link between the two remains fragmented with significant gaps in knowledge. Non-health related topics, such as optimal layouts, financial elements, and regional variations, too often remain separated from the health benefits of blue-green infrastructure, making a cohesive view difficult. There exists a growing body of knowledge about the influence and importance of blue-green infrastructure on our lives and the environment we share. This review aims to gather and evaluate existing PubMed research on the impact of blue-green infrastructure on health during extreme heat events. Synthesizing current research using an ecosystems service approach links blue-green infrastructure's temperature regulation and diffuse cultural services to human health during extreme heat-related physical and psychological stress. Doing so will expose knowledge gaps and provide a comprehensive, health-focused perspective on the efficacy of blue-green infrastructure in mitigating the impacts of extreme heat events. As cities grow and climate change progresses, the ability of blue-green infrastructure to safeguard global health during heat waves warrants critical attention. This literature review adds valuable and original knowledge and will inform future research, policymaking, and practice, contributing to creating resilient, healthy, and sustainable communities.

METHODS

A systematic literature review was done to better understand the role of blue-green infrastructure on health during extreme heat events. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) framework was used for transparency and replication.

Search strategy

The search was limited to articles published in the PubMed database. Search terms describing times of high ambient temperatures (heat dome, heat wave and heatwave, extreme heat, and heat event) were combined with geographic designators common to blue-green- infrastructure (green roofs, green walls, parks, gardens, permeable pavement, rain gardens, green street, urban pond, urban lake, blue space, green space, urban forests). This was then crossed with the general term "health." Results included published articles up to June 2024 and were not limited by location or language. The final search was as follows: (("green roof") OR ("green wall") OR ("urban forest") OR (park) OR (garden) OR (permeable pavement) OR ("rain garden") OR ("green street") OR ("urban pond") OR ("urban lake") OR (green space) OR (blue space) OR ("urban water")) AND (("extreme heat") OR (heatwave) OR ("heat wave") OR ("heat dome") OR ("severe heat")) AND (health).

Selection strategy

Inclusion criteria required articles to have real-life human setting measurements of a health outcome, extreme heat, and blue-green infrastructure. Articles met exclusion criteria if they did not include all three elements (human health measurement, extreme heat measurement, blue-green element measurement). Articles relying on non-real-life settings (calculated estimates like the Physiological Equivalent Temperature or biochemical models) and those not focused on human health were excluded. Finally, academic articles, such as commentaries or policies and methodology analysis, were excluded.

Data extraction

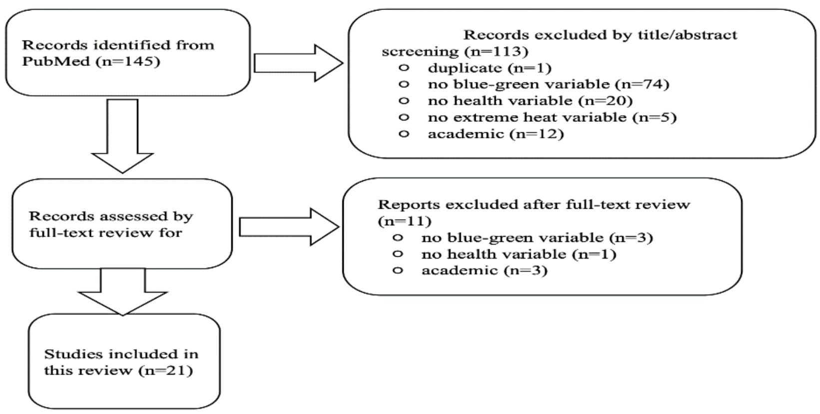
The author reviewed all selected articles in detail. The data was extracted and charted for synthesis. Design, sample, and reported findings were noted for each study. Full titles and author(s) are listed to aid in replication. The blue-green infrastructure measure, extreme heat definition, health outcome, variables controlled, and if statistical significance was reached were listed to aid with synthesis.

RESULTS

Literature search results

A search of the PubMed database yielded 145 articles. The initial title and abstract review excluded 112 articles and found one duplicate. Seventy-four articles did not include a blue-green variable, 20 did not examine a human health outcome, and five did not discuss the impact during extreme heat events. Twelve were academic articles (six focused on methodology, four were commentaries, and two were policy), and one was a laboratory rather than a real-life setting. The remaining 32 articles underwent full-text review. An additional eleven studies were eliminated. Three lacked a blue-green variable, one did not examine a human health outcome, two were commentaries, one focused on methodology, and four simulated a health aspect rather than measuring it directly. Using these criteria, 21 articles were chosen for synthesis. (Figure 1)

Figure 1: PRISMA flow diagram



Description of selected studies

The studies were geographically diverse, spanning four continents: eight from Asia, one each from Australia and Europe, and 11 from North America. All the studies were quantitative, and all, save one, were retrospective. All used an analytic observational design, including seven case-crossover study designs, ten cohort studies, three time-series analyses, and one ecologic study. Details of selected studies are compiled in Table 1.

Table 1: Overview of selected studies

Authors	Title	Design	Sample size	Reported findings
Benmarhnia T, Kihal-Talantikite W, Ragettli MS, Deguen S.	Small-area spatiotemporal analysis of heatwave impacts on elderly mortality in Paris: A cluster analysis approach	analytical observational: ecological	1238 cases / 4632 controls in HWa; 296 cases / 1210 controls in HWb.	Poor AQ (beta=0.02, 95% CI: 0.001-0.045), foreign born (beta=0.614 (95% CI: 0.01-1.22) and blue-collar work (beta-1.28, 95% CI: 0.211-2.348 correlated with increased mortality. Green space density had a protective effect, beta= -0.005 (95% CI: -0.011--0.0001), density of constructed feature increased the risk of dying during a HW, beta= 0.004 (95% CI: 0.001- 0.008) Significance at p<0.10
Gronlund CJ, Berrocal VJ, White-Newsome JL, Conlon KC, O'Neill MS.	Vulnerability to extreme heat by socio-demographic characteristics and area green space among the elderly in Michigan, 1990-2007	Analytical observational: case-crossover time-stratified	8 city groups	Percent non-green space increased the association between EH and cardiovascular mortality for HW >4d at Tmean > 97th percentile. Controlling for other modulators, the odds of cardiovascular mortality in zip codes in the 75th percentile of non-green space (8% green) were 1.18 (95% CI: 1.09-1.28, p<0.001) EH / not EH, whereas zips with only 39% non-green space (61% green) were 0.98 times higher EH/not EH (p>0. 1). There was no association with respiratory mortality. Using Tmax (not apparent T), associations remained (no calculations given).
Gronlund CJ, Zanobetti A, Wellenius GA, Schwartz JD, O'Neill MS.	Vulnerability to Renal, Heat and Respiratory Hospitalizations During Extreme Heat Among U.S. Elderly	Analytical Observation: case-crossover time stratified	109 city groups	2d EH was associated with an 8% (95% CI: 6-11, p<0.01) increase in hospitalizations for renal/heat/respiratory causes with the highest associations with older age, black race and homes built before 1940. 6d EH: 11% increased hospitalizations (95% CI: 8-14, p<0.01) with similarly increased SES modifiers. Having AC nullified the effect of EH, and lack of AC increased hospitalizations by 24% during EH versus nonEH days (95%CI: 17-32, p<0.01). Green space did not modify hospitalizations in any model.
Jiao A, Sun Y, Avila C, Chiu V, Slezak J, Sacks DA, Abatzoglou JT, Molitor J, Chen JC, Benmarhnia T, Getahun D, Wu J.	Analysis of Heat Exposure During Pregnancy and Severe Maternal Morbidity	Analytical Observational: cohort	403602 pregnancies; 3445 cases	A dose-based risk was noted with higher OR for severe maternal morbidity with increased EH exposure. ≥2d at 75th percentile OR=1.32; 95% CI: 1.17-1.48, p < 0.001 and ≥4d at 95th percentile OR=2.39; 95% CI: 1.62-3.54, p < 0.001. Lower education increased risk (OR=1.43; 95% CI, 1.26-1.63; p< 0.001). Consistently higher (nonsignificant) associations were found for older, Hispanic, lower income, smoking, and less exposure to trees/grass.
Jiao A, Sun Y, Sacks DA, Avila C, Chiu V, Molitor J, Chen JC, Sanders KT, Abatzoglou JT, Slezak J, Benmarhnia T, Getahun D, Wu J.	The role of extreme heat exposure on premature rupture of membranes in Southern California: A study from a large pregnancy cohort	Analytical Observational: cohort	190767 cases	Premature rupture of membranes was positively associated with HW (40°C >4d), HR=2.00, 95% CI: 1.24–3.25, p<0.05). For younger mothers, green space significantly correlated with AQ factors, heat index and daily Tmax. Positive trends between the percentage green space and premature rupture of membranes were noted at higher temperature durations.
Pan R, Song J, Yi W, Liu J, Song R, Li X, Liu L, Yuan J, Wei N, Cheng J, Huang Y, Zhang X, Su H.	Heatwave characteristics complicate the association between PM (2.5) components and schizophrenia hospitalizations in a changing climate: leveraging of the individual residential environment	Analytical Observational: case-crossover individual-level time-stratified	160736 total hospitalizations; 546192 control days; 1630 cases in HW 4d >99th percentile; 26824 in HW 2d>90th percentile	One unit increase in black carbon increased hospitalization risk by 1.59% (95% CI: 0.95–2.23). Synergistic association between hospitalizations and increasing intensity and duration of HW. High-percentage green spaces were associated with higher AQ. HW incidence was lowest in blue areas. Grey areas had the lowest AQ and most frequent HW. Green and blue areas had lower hospitalization compared to grey spaces. Dose-response relationship: risk decreases with an increasing percentage of green and blue spaces, with protective effect when green and blue spaces exceed 17.6% of the total area (decreased BC). Excluding 2020, results remained stable. Significance defined at p<0.05
Schinasi LH, Bloch JR, Melly S, Zhao Y, Moore K, De Roos AJ.	High Ambient Temperature and Infant Mortality in Philadelphia, Pennsylvania: A Case-Crossover Study	Analytical Observational: case-crossover time-stratified	1522 total deaths	The risk of infant mortality increased linearly with daily Tmin > 95th percentile. The risk of infant mortality increased by 22.4% (95% CI: 5.0-42.6) for every 1°C above 23.9°C No observed evidence of effect modification by any covariates. Two modifiers approached significance but without expected dose relationship. OR of mortality during HW in infants with >16% tree canopy was 61.5, 95% CI: 21-116, p=0.08. OR for between 11-16% tree cover was 2.5, 95%CI: -28-46 and for less than 7% was -5.3, 95%CI: -35-38. Population density followed a similar chaotic pattern, p=0.06. Significance defined at p<0.05
Sewell K, Paul S, De Polt K, Sugg MM, Leeper RD, Rao D, Runkle JD.	Impacts of compounding drought and heatwave events on child mental health: insights from a spatial clustering analysis	Analytical Observational: time series ecologic study	1122 high-risk area/1516 low-risk area HW, 778/997 drought, 167/274 both with mood disorders; 529/816 HW, 568/342 drought, 138/126 both with suicidal ideation cases	The risk of a suicide-related admission during a HW was 1.33 times the risk compared to a non-heatwave in Charlotte, NC. Pediatric mood disorder admissions were 29% higher during HW compared to a non-HW period in Charlotte, Lumberton and Fayetteville. Visits for suicide and mood disorders in youth were 4.48 and 6.32 times higher compared to non-drought periods in the mountains and coast. (p<0.001) The percentage of total green space had an importance of 78.59 on mood in HW, but only 1.32 for droughts and 5.59 for their coincidence. For suicide, 100 with HW, none for draughts, and 100 for both.
Sun Y, Ilango SD, Schwarz L, Wang Q, Chen JC, Lawrence JM, Wu J, Benmarhnia T.	Examining the joint effects of heatwaves, air pollution, and green space on the risk of preterm birth in California	Analytical Observational: cohort	1967300 births total; 127039 preterm births (PTB); 4975 extremely PTB; 11894 very PTB; 114949 late PTB	Tmean was higher and AQ lower in southern verses northern California. HW and NDVI scores had negative additive interactions (RERIs <0) for less intense heatwaves (HWD1-7) and RERI>0 for more intense heatwaves (HWD8- 12). Additive interactions were observed between HW and decreasing tree canopy levels. Synergistic effects for HW with low AQ and low NDVI. RERIs of the tree canopy cover showed positive additive interactions, even for less conservative HW definitions. None significant.

Wang L.	Mediating Effect of Heat Waves between Ecosystem Services and Heat-Related Mortality of Characteristic Populations: Evidence from Jiangsu Province, China	analytical observational: time-series	3 cities, 25.8 million total population in 2010	Positive association between HW and mortality. Negative correlations between all variables and HW mortality except SHDI. Trees (CS -.0.658, p<0.01), biodiversity (COHESION -0.526, p<0.01), cooling green spaces (NDVI -0.394, p<0.05), water presence (WY -0.393 p<0.05) and cultural service (SHDI +0.599, p<0.01) have significant correlation with HW mortality. The mediating effects of CS were stronger in cardiorespiratory diseases, the elderly and women.
Wang Y, Bobb JF, Papi B, Wang Y, Kosheleva A, Di Q, Schwartz JD, Dominici F.	Heat stroke admissions during heat waves in 1,916 US counties for the period from 1999 to 2010 and their effect modifiers	Analytical Observational: cohort	23.5 million participants per year residing in 1,916 counties; 119,817 heat wave days in 1,916 counties	Overall RR of heat stroke on HWd (>97th, 2d) compared to matched non-HWd was 11.0 (95 % CI: 8.8–13.6, p<0.05). RR of heat stroke on HWd compared to matched non-HWd decreased from 71.0 (95% CI:21.3–236.2, p=0.03) in 1999 to 3.5 (95% CI: 1.9–6.5) in 2010. RR decreased by 28% (95% CI: 9-43) per 10% increase in central AC prevalence. NDVI, urbanicity, mean summer temperature, humidity, wind speed, cloud cover, or ozone concentration did not modify the association between heat stroke admissions and HWd
Ye T, Guo Y, Huang W, Zhang Y, Abramson MJ, Li S.	Heat Exposure, Preterm Birth, and the Role of Greenness in Australia	Analytical Observational: cohort	1225722 births; 63144 PTB	Compared with no EH, exposure to daily EH and nighttime EH in the 3rd trimester was associated with increased risks of PTB, OR =1.61 (95% CI: 1.55-1.67) and 1.51 (95% CI: 1.46-1.56). lower odds of PTB among pregnant individuals residing in greener areas. Improving NDVI and tree cover could reduce daily EH-associated PTB by 13.7% (95% CI: 2.3-15.1) and 20.9% (95% CI, 5.8-31.5), respectively. For nighttime EH-associated PTB, reductions were 13.0% (95% CI: 0.2-15.4) and 17.2% (95% CI: 4.1-27.0), respectively. interaction of heat with NDVI and tree cover were significant for day Δβ= -0.961 (95% CI: -0.075- -1.847, p=0.033) and -0.012 (95% CI: -0.003- -0.021, p=0.011), and night T Δβ= -0.955 (95% CI: -0.126- -1.783, p=0. 024), -0.012 (95% CI:-0.004- -0.20, p=0.004)
Zhang H, Liu L, Zeng Y, Liu M, Bi J, Ji JS.	Effect of heatwaves and greenness on mortality among Chinese older adults	Analytical Observational: cohort	20758 participants, totaling 66923 person-years	Mortality and highest HWd by NDVI had HR=1.04 (95% CI: 1.02-1.05) In urban areas, a 0.1-unit decrease in NDVI was associated with an 8% increase in the risk of mortality, and rural HR = 1.04 (p<0.005). The risk of death during heat was higher for females (HR = 1.06) than males (HR = 1.02) >100yo had the greatest risk HR 1.07. HR for each 3-day increase in HWd was 1.04 (95% CI: 1.04-1.05), and per 0.1-unit decrease in cumulative NDVI, HR = 1.06 (95% CI: 1.05-1.07, p<0.001). HR for the interaction term between each 3-day increase in HWd and 0.1-unit decrease in cumulative NDVI was 1.01 (95% CI: 1.01-1.02, p<0.001)
Zhou W, Wang Q, Li R, Kadier A, Wang W, Zhou F, Ling L.	Combined effects of heatwaves and air pollution, green space and blue space on the incidence of hypertension: A national cohort study	Analytical Observational: cohort	6448 participants totaling 20,836.8 person-years	Among participants who developed hypertension, more participants had individual HW experiences. Multiplicative interaction between HW and residential greenness was positive and statistically significant (HR = 1.14, 95%CI: 1.04–1.25, p<0.05). The synergistic effect of HW with lack of green space was more significant in females, educated participants, and elderly <80 years. No significant interaction between HW exposure and blue spaces. RERIs of HW and lack of green space on hypertension: HW5 (RERI = 0.32, 95%CI: 0.06–0.59), HW7 (RERI = 0.42, 95%CI: 0.20–0.64) and HW8 (RERI = 0.40, 95%CI: 0.13–0.66) p<0.05.
Zhou W, Wang Q, Li R, Zhang Z, Kadier A, Wang W, Zhou F, Ling L.	Heatwave exposure in relation to decreased sleep duration in older adults	Analytical Observational: cohort	7,240 participants	Sleep duration decreased by 1, 1.5, and 2 hours for 38%, 24%, and 22% of participants. 5% showed an excessive decrease in sleep duration. Significant relationships between the increase in HW events and decreased sleep duration were detected (OR = 1.030, 95 %CI: 1.003–1.057) No significant modifying effects of AQ and green space. Compared to individuals in regions experiencing a decrease or minor increase in NDVI, those in areas with rising NDVI values were less likely to experience an excessive decrease in sleep duration. (no calculation given) Significance defined at p<0.05
Zhou W, Wang Q, Li R, Zhang Z, Wang W, Zhou F, Ling L.	The effects of heatwave on cognitive impairment among older adults: Exploring the combined effects of air pollution and green space	Analytical Observational: cohort	19,419 individuals totalling 43,401 person-years	HW exposure was associated with higher risks of cognitive impairment, ranging from 3.5 % (HR=1.035, 95% CI: 1.016–1.055) to 5.8 % (HR=1.058, 95% CI: 1.040–1.075) Underlying dose-response relationship between heatwave intensity and the risk of cognitive impairment with HW ≥2d. For green space, a significant combined effect of lack of green space exposure and HW in a multiplicative scale was observed, HR from 1.009 (95% CI:1.000–1.018) to 1.013 (95% CI,1.002–1.025). Participants lacking green space and experiencing heatwave exposure had a higher risk of cognitive impairment (RERIs >0) than their references. Significance defined at p<0. 05

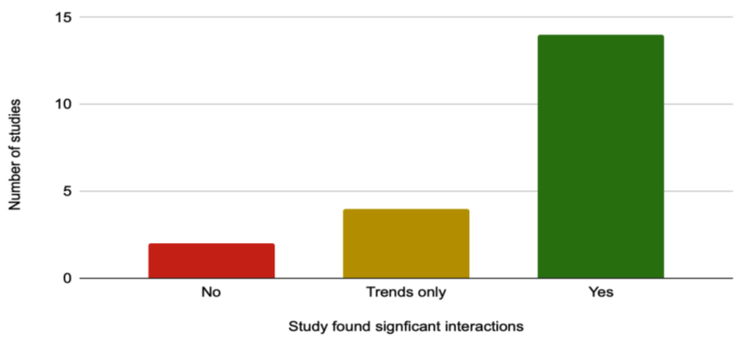
Abbreviations: AC = air conditioning; AQ = air quality; CI = confidence interval; d = day; EH = extreme heat; HR = hazard ratio; HW = heat wave; NDVI = normalized difference vegetation index; PM = particulate matter in microns; OR = odds ratio; RR = relative risk; SES = socioeconomic status; T = temperature

Seven measured blue-green spaces at the residential or personal level, while the rest used regional averages. Heat wave definitions varied, but all studies evaluated a maximum temperature of at least the 75th percentile. Baseline temperature scales differed with study characteristics. Daytime maximum or mean temperatures were used most. Studies looking at infant health and sleep used a maximum nighttime temperature. Topics evaluated included overall mortality or population-specific (infants and adults over 65 years old), mortality, and specific health concerns: mental health, mother/baby health, hypertension, heat injury, respiratory emergency, physical activity and sleep. Seven studies considered a blue-green element a central part of the study, and 14 included it as a potential modifying element. Table 2 is a synthesis matrix of inclusion criteria, variables controlled in each study and whether the study found significant associations between blue-green infrastructure and health outcomes.

Selected study findings

Eighty-six percent of the selected studies found statistically significant interactions (14 of 21) or nonsignificant but similar trends (4 of 21) between blue-green elements and health during extreme temperatures. Three found no interaction at all. (Figure 2) Of those finding significant associations, 44% evaluated mortality and 29% mental health.

Figure 2: Findings for significant interaction between blue--green infrasturucture and health during extreme heat



<u>Mortality and blue-green infrastructure during extreme heat</u>

Six studies found statistically significant positive associations between blue-green infrastructure density and mortality during heat waves. All accounted for socioeconomic variables. Studies found that either increased blue-green infrastructure was associated with decreased mortality,[25] low levels of blue-green infrastructure were associated with increased mortality,[26–28] or both were true.[29,30] In the United States, Michigan residents living in zip codes with less than 8% green space had 1.18 times the odds of cardiovascular mortality during a heat wave (95% CI: 1.06-1.29, $p<0.001$) compared to non-heat wave days. Individuals with more than 61% green space in their zip code had nonsignificant but protective relative odds (OR=0.98, 95% CI: 0.89-1.07).[28] The odds of dying during extreme heat in New York City were lower in areas with higher than average grass and shrubs (OR=0.96, 95% CI: 0.94-0.99, $p<0.05$).[25] In Paris, France, each unit increase in vegetation density decreased the risk of death for those aged 65 and over during a heat wave by 0.005 units (95% CI: -0.011 to -0.0001, $p<0.1$), while the density of constructed features (buildings, roads) increased mortality by 0.004 units (95% CI: 0.001 to 0.008, $p<0.1$).[29] A low proportion of green areas around public buildings (OR=1.178, 95% CI: 1.016-1.366, p undefined) or rooftop green areas (OR=1.207, 95% CI: 1.042-1.399, p undefined) was associated with increased mortality among individuals with low education in Seoul, South Korea.[27] Finally, a study conducted across diverse regions of China found that each 0.1 unit decrease in measured greenness had a mortality hazard ratio of 1.06 (95% CI: 1.05-1.07, $p<0.001$).[26] Wang et al. (2023)

evaluated the effectiveness of individual elements of green-blue spaces in reducing mortality risk in adults over the age of 65 during heat waves. They found that the availability of free water (OR: -0.393, p<0.05), plants that sequester carbon (OR: -0.658, p<0.01), and connected green ecosystems (OR: -0.526, p<0.001) were protective factors and low area percentage vegetation (OR: 0.394, p<0.05) increased risk.[30] Although not a direct measure of morbidity, developing hypertension, often a precursor to heart disease, was associated with a lack of green space during heat waves in China (HR = 1.14, 95% CI: 1.04-1.25, p<0.05). The relative excess risk due to the interaction between heat waves and lack of green space was 2.28 (95% CI: 1.79-2.90, p<0.05).[31] It is important to note that these studies demonstrate a correlation between heat and health but cannot clearly demonstrate causation due to the mirade of factors that influence an individual's health. Underlying individual causes of death are varied, however the association between green space and lower mortality rates should not be dismissed.

Mental health and blue-green infrastructure during extreme heat

Tree canopy provided statistically significant protection against mood-related emergencies (p = 0.01),[32] while a lack of green space contributed to greater cognitive decline in seniors (HR = 1.01, 95% CI: 1.00-1.03, p<0.05).[33] Residences with more than 17.6% vegetation had a protective effect against schizophrenic hospitalizations during extreme heat (p<0.05).[34] Among suspected mental health modifiers in individuals aged 6 to 24, the level of greenness was second only to home crowding in predicting suicide risk during heat waves, and it was the most influential factor when heat waves and droughts occurred simultaneously.[35] Similar to mortality, mental health is a multifaceted condition within which access to green spaces appears to play a protective role against measurable poor outcomes such as cognitive decline and suicide.

Children's health and blue-green infrastructure during extreme heat

An observational prospective cohort study in Austin, TX, found that while activity levels decreased with increasing temperatures, children who had recess at the park with the greatest tree canopy had six percentage points more moderate to vigorous physical activity than those with the lowest tree cover (95% CI: 2.1-9.9, p<0.01).[36] For heat-related respiratory admissions for children under five years old in Hanoi, Vietnam, increasing the green space ratio by 1% decreased the overall heat-related hospitalization risk by 3.8% (p=0.006). The impacts were more profound in urban areas, where green space decreased the risk by 5.2% (p=0.014).[37] A large study from Australia suggested that improved vegetation and tree cover could reduce premature births by 13.7% (95% CI: 2.3%-15.1%) and 20.9% (95% CI: 5.8%-31.5%), respectively.[38]

Characteristics of nonsignificant studies

Three of the four studies that found only nonsignificant trends for the interaction of blue-green infrastructure with health during heat waves focused on mother-baby health.[39–41] The fourth study evaluated sleep patterns.[42] Two studies by Jiao et al. from 2023 calculated address-level greenness using online images rather than satellite-based photosynthesis measurements such as the Normalized Difference Vegetation Index. Both studies reported nonsignificant positive associations between greenness and heat wave risk in severe maternal morbidity[39] and premature rupture of membranes.[40] Another study of premature births in California found tree canopy potentially protective, especially at higher temperatures,[41] and individuals sleeping in areas with higher vegetation scores tended to be less affected by heat wave conditions.[42] However, neither obtained statistical significance. The three studies that found no interaction between blue-green infrastructure and health during heat events evaluated adult heat injury[43,44] and infant mortality.[45] The studies on heat injury used large spatial areas to determine green space, which the authors noted may have impacted the results.[43,44] A Philadelphia study on infant mortality during heat waves found no significant associations or consistent trends with blue-green infrastructure. No modifying variables, including infant age, poverty level, or race, reached significance, which the authors attributed to sample size.[45]

DISCUSSION

Main findings

Blue-green infrastructure positively impacts human health during times of extreme heat. The lack thereof is associated with a higher risk of poor health outcomes,[26–31,33,35] and its presence mitigates the detrimental effects of extreme heat.[25,28–30,32,34–38] Although the statistical significance in each study was often small, the cumulative effect suggests that greater integration of blue-green infrastructure into our global communities could protect millions of people from the detrimental effects of extreme temperatures.

Explanations and implications

The positive effects of blue-green infrastructure are multifactorial,[23] including lowering temperatures,[20,21] removing air pollutants,[19] increasing social interaction and decreasing stress.[4] Air quality and social isolation are independent risk factors during heat events.[18] These overlaps likely contribute to the effect we found in this synthesis. The implications of this review and studies like it cannot be overstated. Established data for effective methods of heat abatement are paramount in our quickly changing world.[2,5] Understanding the effects of green infrastructure on fundamental measures of human and non-human ecosystem health is crucial for building sustainability and climate resilience policies with proven benefits. As the climate changes, our ability to adapt to hotter temperatures must progress. Implementing effective, sustainable solutions that do not contribute to CO_2 emissions is essential.[46] Blue-green infrastructure is a locally accessible, cost-effective, win-win investment that benefits all ecosystems, including humans.[48]

Strengths and limitations

The strength of this review lies in the diversity of studies available. Consistent results were found globally, in diverse settings, and across multiple health outcomes. The various definitions for extreme heat and different methods of measuring blue-green infrastructure further strengthen our findings. Statistically significant effect sizes were often very small. However, their cumulative effect strongly implies a true association exists. The initial search parameters included thirteen commonly used terms to describe blue- green infrastructure and five terms describing extreme heat. However, this list may have missed additional industry terminology, affecting our results. Also, this literature review was constrained to the PubMed database. This enabled a health focus, but because the data on blue- green infrastructure comes from diverse sources, the possibility that we missed significant findings that were not published through PubMed creates a potential limitation to our conclusions. Historical inequity plagues the distribution and quality of urban parks and waterways.[24,49] The majority of the studies reviewed took caution to adjust for socioeconomic confounders such as race, income, and education. Nevertheless, extreme heat affects well-being in many ways, and there are diverse socioeconomically driven elements affecting heat coping mechanisms not explored here, such as the safety and cleanliness of available spaces and occupational hazards.[4] The availability of other means of heat management was only included in three of the studies we reviewed. Lastly, the availability of heat adaptation methods does not equate to use. The effect of green-blue spaces may differ with their accessibility and quality.[4,48]

Future research

This review found that blue-green infrastructure positively impacts health during extreme heat and presented evidence that even small increases in vegetation generate positive outcomes.[26,29,37,38] However, urbanized areas of high heat (urban heat islands) and vegetative cooling occur at the local level.[8,20] Fourteen of the 21 reviewed studies used regional averages, which may have masked a more profound effect. This presents a vital aspect of future study for local health and resiliency policies. Additionally, many of the studies in this review looked only at green vegetation. The interaction between urban water bodies with health warrants more exploration.[21] Some research shows that types of nature affect an area differently,[22] so understanding how much and which types of vegetation or water sources are needed to make the maximum difference in health remains an important area of exploration. Quantifying the cost-benefit of using scarce water supplies to cultivate native plants and ecosystem diversity for human health would advance the work of both climate activists and public health officials. This synthesis supports ecomanagement trends towards urban greening but also highlights the scarcity of available health-related efficacy research. Much of the research on blue-green infrastructure and most of the studies included in this review focus on the developed world.[22] While climate change causes global disruption, a disproportional burden is held in less developed regions of Africa, Central America and South America.[4,9] A more inclusive understanding of effective climate change adaptation is needed through collaborative projects that focus on community strengths. The United Nations places water cycle disruptions at the center of the climate crisis. Water scarcity is a reality for half the world's population, and droughts are becoming increasingly severe.[50] While native nature-based solutions serve as a partial solution to extreme heat, more data is needed to effectively allocate and manage water sources for reliable sustainability.

CONCLUSION

Integrating blue-green infrastructure into public health and urban planning is a critical strategy for mitigating the adverse health effects of extreme heat. Individual study result showed small but consistent evidence of blue green infrastructure ability to provide health benefits during extreme heat. The consolidated evidence creates a compelling argument for increased support of green roofs, urban forests, community green spaces and all the many interconnected elements of blue-green infrastructure. Policymakers and urban planners must prioritize developing and maintaining green and blue spaces to safeguard public health in the face of escalating global temperatures.

Table 2: Selected studies synthesis matrix of inclusion criteria, controlled variables and level of significance reached

Lead Author	Health outcome	Green measure	Heat wave definition	Controlled variables	Significance
Benmarhnia T	mortality, adult >65 years old	Regional - census block as modifer	Tmax 31°C (daytime) / Tmin 21°C (nighttime)	age, income, education, low-income housing, occupation, and immigration status	Yes +BGI ≈ health benefit and -BGI ≈ health detriment
Gronlund CJ	mortality, adult >65 years old	Regional - census block as modifer	97th and 99th percentile of Tmean ≥ 4d	personal marital status, age, race, sex and education, age, race, income, education, living alone, and housing age	Yes -BGI ≈ health detriment
Gronlund CJ	heat injury: emergency hospitalization	Regional - census block as modifer	97th percentile of Tmax either 0-1d or 2-5d	sex, race/ethnicity, age, housing age, air conditioner presence, education, income	No
Jiao A	mother-baby: severe maternal morbidity	Local - residential address, as modifier	75, 90 and 95th percentile daily Tmax ≥ 2-4d	maternal age, race/ethnicity, education level, income level, year of delivery, and season of conception	Trends only
Jiao A	mother-baby: premature rupture of membranes	Local - residential address, as modifier	75, 90, 95, 98th percentile Tmax ≥ 2-4d	race/ethnicity, education, income, BMI, smoking, birth year, parity, air quality, population level air conditioner ownership	Trends only
Kim EJ	mortality	Regional - census block as modifer	95th percentile Tmax ≥ 2d	sex. marital status, education, employment, regional deprivation index, hospital proximity, air quality	Yes -BGI ≈ health detriment
Lanza K	children: physical activity	Local - directly measured for location as independent variable	≥ 33°C	all three sites were elementary schools in low socioeconomic, predominately Latino neighborhoods	Yes +BGI ≈ health benefit
Lavigne E	mental health: emergency department visits for mood or behavioral disorders	Regional - census block as modifer	97.5th percentile Tmean	income, race, urban residence, and rated health as poor. Material and Social Deprivation Index (employment, ave income, education, and living arrangement). air quality	Yes +BGI ≈ health benefit
Madrigano J	mortality	Regional - census block as modifer	heat index (ambient T and relative humidity) or Tmax >95°F ≥ 2d	sex, race, age, birth origin, location and cause of death, non-English speaking, public assistance	Yes +BGI ≈ health benefit
Nguyen VT	children: respiratory-related hospital admission	Regional - census block as modifer	99th percentile Tmean	sex, age, location and population density	Yes +BGI ≈ health benefit
Pan R	mental health: schizophrenia hospitalization	Local - residential address, as modifier	90, 92.5, 95, 97.5, 99th percentile of Tmax ≥ 2-4d	air quality (PM2.5, SO4, NO3, NH4, organic matter and black carbon), age, gender,	Yes +BGI ≈ health benefit

Schinasi LH	mortality, infant	Local - residential address, as modifier	95th percentile of Tmin = 23.9°C	date and age of death, location, maternal race/ethnicity, infant sex. age of housing, population density	No
Sewell K	mental health: psychiatric emergency department visits	Regional - census block as modifer	90th percentile of Tmean ≥ 3d	age, race, ethnicity, sex, medical insurance payor, access to a vehicle, household occupancy rate and type, English proficiency, internet access	Yes +BGI ≈ health benefit and -BGI ≈ health detriment
Sun Y	children: preterm birth	Regional - census block as modifer	75, 90, 95, 98th percentile of Tmax for ≥ 2-4d	maternal age, race/ethnicity, education, health insurance, parity, infant sex and season of birth, air quality	Trends only
Wang L	mortality	Regional - census block as modifer	90th percentile of Tmax ≥ 2d	sex, age, cause of death, location	Yes +BGI ≈ health benefit and -BGI ≈ health detriment
Wang Y	heat injury, adults >65 years old	Regional - census block as modifer	97th percentile of Tmean ≥ 2d	air quality, cloud cover, wind, air conditioner, urbanicity location, age	No
Ye T	children: preterm birth	Local - residential address as modifier	95th percentile of location nocturnal (2000-0700) Tmean	gestational age, sex, smoking, conception season, parity, immigration status, co-morbidities (chronic hypertension or gestational diabetes), area-level population density and demographics, birth year	Yes +BGI ≈ health benefit
Zhang H	mortality, adult >65 years old	Local - residential address as independent variable	92.5th percentile of Tmax ≥ 2d	air quality, age, gender, geographic region, ethnicity, marital status, urban/rural residence, education, occupation, smoking status, alcohol consumption, and physical activity	Yes -BGI ≈ health detriment
Zhou W	hypertension, adults >65 years old	Regional - census block as modifer	92.5, 95, 97.5th percentile of Tmax ≥ 2-4d	air quality, age, gender, rural/urban, income, education, salt intake, marital status, geographic region, smoking, drinking, exercising, BMI	Yes -BGI ≈ health detriment
Zhou W	sleep, adults	Regional - census block as modifer	90, 92.5, 95, 97.5th percentile of Tmax ≥ 2-4d	sex, age, education, economic status, marital status, urban/rural, geographic region, smoking, drinking, napping, weight control, comorbidities (hypertension, diabetes, depression)	Trends only
Zhou W	mental health: cognitive ability, adults	Regional - census block as modifer	92.5, 95, 97.5th percentile of Tmax ≥ 2-4d	Age, gender, rural/urban, smoking, drinking alcohol, exercising, geographic region, income, education, marriage, social and leisure activity. Percentage population low education, low income, homes without running water, toilets, kitchens or showers. air quality	Yes -BGI ≈ health detriment

BGI = blue-green infrastructure; BMI = body mass index; d = day; PM = particulate matter in microns; T = temperature

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