How to organize Green Nature Based Solutions in Cities for Elderly People and those with Chronic Conditions

The aim of this study is to explore the urban organization of nature-based solutions that are designed to protect older people and those living with chronic conditions. The city's layout is examined in relation to the varying abilities of these social groups to reach key locations – such as those required for daily life – during a heatwave. While general European policies do protect populations from urban climate change, they often fail to assess the most vulnerable groups, leaving their protection to specific policies. The approach taken here is that the protection of the most vulnerable should be an integral part of planning in ordinary urban policies, rather than a separate chapter to be addressed surreptitiously. This should be incorporated at the design stage, rather than being left more to the discretion of enlightened administrations. To this end, a common clinical approach was used: the six-minute walk test, to determine the maximum distance that can be covered by an 82-year-old person with Type 2 diabetes, autonomic neuropathy (sweating difficulties and limited heat dissipation), and early-stage cataracts, which increase anxiety when moving around the city. After analyzing these conditions, we assessed how street furniture, if suitably equipped, could meet this group's needs, thereby making the city more inclusive for them. Results indicate mobility reductions of up to 40% across vulnerable cohorts, while targeted Nature-Based Solutions can reduce mean radiant temperature by up to 18°C, significantly restoring walking capacity and lowering critical thermal risk thresholds.

Keywords: *urban climate, fragile population, heat wave, nature-based solutions, health determinants*

Introduction

In an era defined by accelerating climate change, extreme weather events have increased in both frequency and intensity, transforming heatwaves from occasional seasonal anomalies into one of the most lethal environmental hazards of the twenty-first century (Changnon et al., 1996; IPCC, 2022). This crisis is profoundly amplified within contemporary cities due to the Urban Heat Island (UHI) phenomenon, a microclimatic modification where dense configurations of asphalt and concrete, coupled with anthropogenic heat emissions, trap solar radiation and prevent nocturnal cooling (Georgiadis, 2017; Nardino et al., 2022). As a result, urban centers experience significantly higher temperatures than their rural surroundings, turning metropolitan areas into epicenters of climate risk (McMichael, 2000; Masselot et al., 2024). Crucially, the impacts of these elevated thermal regimes are not distributed uniformly across the urban fabric (Meerow and Mitchell, 2017; Tschakert et al., 2025). Instead, extreme heat acts as a powerful threat multiplier, exposing deep-seated socioeconomic, physical, and demographic fractures by disproportionately impacting society's most vulnerable populations, with the elderly and disabled at the forefront of this crisis (Davies and Harwood, 2023; Chakraborty, 2025).

The acute vulnerability of older adults and fragile cohorts to thermal stress is rooted in a complex intersection of biological degradation and social precarity (Cremonini and Georgiadis, 2025; Prina et al., 2024). From a physiological perspective, aging inherently diminishes the human body’s capacity for thermoregulation and alters thirst perception, rendering older individuals highly susceptible to dehydration, heat exhaustion, and fatal heat stroke (Koppe et al., 2004; De Gea Grela et al., 2024). These age-related vulnerabilities are further compounded by a high prevalence of pre-existing chronic conditions—such as cardiovascular, respiratory, and metabolic diseases—as well as the use of medications that interfere with normal sweat production (Sisodiya et al., 2024). However, biological susceptibility represents only one facet of the problem; it is heavily exacerbated by social determinants of health and deep-seated inequities (European Commission, 2023; Holland et al., 2024). Marginalized urban residents, particularly isolated seniors, often inhabit substandard housing characterized by poor insulation and lack of mechanical ventilation (Poumadère et al., 2005). Financial constraints further lead to energy poverty, forcing vulnerable individuals to ration or entirely forgo air conditioning due to the prohibitive cost of electricity (Lund et al., 2010). This combination of physical frailty and socioeconomic deprivation creates a dangerous synergy, effectively trapping fragile populations in indoor or localized outdoor environments that offer no respite from the soaring outdoor temperatures (Conti et al., 2005; Ballester et al., 2023).

As global demographic trends point toward an increasingly urbanized and rapidly aging world population, the convergence of intense urban heat, physiological degradation, and heightened psychological stress presents a critical challenge for public health, equity, and municipal governance (WHO, 2024; Baecker et al., 2025). Beyond immediate physical trauma, the exposure to prolonged heat stresses mental well-being, disrupting sleep, altering neurological pathways, and intensifying eco-anxiety and social isolation among frail populations (Cianconi et al., 2020; Pihkala, 2022). Historically, mitigating indoor heat stress has relied heavily on mechanical, energy-intensive cooling technologies, an approach that remains fundamentally unsustainable (World Health Organization, 2022). The widespread adoption of traditional air conditioning units drives electricity demands, intensifies anthropogenic heat rejection into the immediate urban surroundings, and fuels a vicious cycle of greenhouse gas emissions (Georgiadis, 2018). Addressing this public health emergency therefore demands a paradigm shift away from reactive, individualized cooling strategies and toward proactive, systemic interventions capable of modifying the urban microclimate itself (Cremonini et al., 2022). To ensure long-term resilience and spatial justice for the most exposed citizens, modern urban planning must prioritize sustainable, inclusive design frameworks aligned with global developmental guidelines (The Sustainable Development Agenda; Legislative Decree 62/2024—Italian Republic). Within this context, this paper focuses on the evaluation and implementation of Nature-Based

Solutions (NBS) as a strategic infrastructure capable of mitigating the urban heat island effect, restoring ecological balance, and safeguarding both the physical and mental health of vulnerable urban populations (Xu et al., 2025).

Methodology

The primary objective of this methodological framework is to establish a quantifiable, spatially explicit model that evaluates the physiological vulnerability of fragile urban populations, specifically the elderly and individuals with pre-existing chronic conditions, when subjected to extreme heat stress during routine outdoor mobility (Foshag et al., 2024). To achieve this, the methodology bridges urban microclimate simulation with human bioenergetics, utilizing the 6-Minute Walk Test (6MWT) as a foundational standardized metric for physical exertion (Sánchez-González and Osorio-Arjona, 2025). Rather than treating the urban population as a homogenous entity, this approach introduces a series of calibrated physiological adjustment coefficients that scale the metabolic cost, thermoregulatory capacity, and cardiovascular strain based on specific pathologies, age-related degradation, and functional limits (Cremonini et al., 2025a). By coupling the empirical parameters of the 6MWT with localized environmental variables, the methodology simulates how a thermal wave alters the walking capacity and heat-storage rates of distinct vulnerable cohorts, ultimately allowing for a precise evaluation of where and how Nature-Based Solutions (NBS) can be deployed to mitigate these localized risks (Nardino et al., 2021).

The foundational baseline of the human mobility component relies on the parameters derived from the 6-Minute Walk Test, a widely accepted clinical tool used to assess functional exercise capacity in populations with respiratory, cardiovascular, or physical impairments. In a standard clinical setting, the 6MWT measures the maximum distance an individual can walk at a self-selected pace on a flat, hard surface within a six-minute timeframe. In this methodology, the baseline 6MWT distance (6MWDbase) is converted into an average walking velocity (vbase) and serves as the proxy for routine pedestrian movement in the urban environment. However, when transposed from a controlled indoor clinic to an outdoor urban space experiencing a heatwave, this baseline performance must be dynamically adjusted (Håkansson et al., 2018). The outdoor environment introduces thermal stressors—namely high ambient air temperature, elevated relative humidity, low wind speed, and intense mean radiant temperature amplified by the urban heat island effect—that increase the physiological cost of walking (Nardino et al., 2022). Consequently, the actual velocity (vactual) in the simulation becomes a function of both the baseline physical capacity of the individual and the local Universal Thermal Climate Index (UTCI), which quantifies the environmental heat load (Kalkstein et al., 2008).

To accurately model the metabolic energy expenditure (M) during this urban locomotion, we employ a modified bioenergetic equation where metabolic rate is a function of walking speed, body mass, and environmental heat strain. Under temperate conditions, walking at a self-selected pace requires a predictable metabolic cost; however, under extreme thermal stress, the body must divert a significant portion of cardiac output away from the working muscles and toward the skin for heat dissipation via sweat evaporation and vasodilation. This physiological trade-off reduces muscular efficiency and accelerates fatigue, effectively shortening the simulated walking distance (Howard et al., 2024). To mathematically capture this phenomenon across diverse vulnerable groups, we introduce a universal heat-strain reduction factor (αheat), which acts as a modifier on the baseline velocity. This factor is derived from empirical climate-ergonomics data, establishing that for every degree Celsius increase in UTCI above a critical threshold of 32°C, walking velocity decreases non-linearly due to the compounding effects of thermal discomfort and cardiovascular strain (Kalkstein et al., 2011).

The core innovation of this methodology lies in the implementation of specific pathology-dependent coefficients (βpathology) that further modify the baseline metabolic equations and thermoregulatory limits. It is well-established that an elderly individual with chronic obstructive pulmonary disease (COPD) responds to thermal and physical stress completely differently than an elderly individual with congestive heart failure or diabetes (Kang et al., 2024a). Therefore, the model categorizes the vulnerable urban demographic into four distinct cohorts, each governed by a specific coefficient matrix that alters three primary physiological variables: sweat evaporation efficiency (ηsweat), maximum cardiac output allocation for skin blood flow (Qskin), and the metabolic efficiency exponent (γ). For the healthy elderly cohort, the coefficient accounts for the natural senescent decline in autonomic thermoregulation, characterized by a delayed onset of sweating and a reduced vascular compliance that limits skin blood flow by approximately 20% to 30% compared to younger adults (Prina et al., 2024).

When modeling the cardiovascular cohort—specifically individuals with ischemic heart disease or chronic heart failure—the pathology coefficient (βcardio) drastically restricts the maximum allowable Qskin. Because these individuals possess a compromised stroke volume, their cardiovascular system cannot safely sustain the dual demand of supplying oxygen to the locomoting lower limbs and pumping blood to the periphery for cooling (Semenza et al., 1999). In the bioenergetic simulation, this restriction manifests as a rapid elevation in core body temperature (Tcore) at lower walking velocities, triggering a simulated termination of the walk well before the six-minute threshold is reached to prevent a catastrophic cardiovascular event (Guolo et al., 2022). For the respiratory cohort, encompassing patients with COPD or severe asthma, the coefficient (βrespir) adjusts the metabolic cost of breathing. In hot, humid conditions, the density of the air and the hyperventilation triggered by thermal stress significantly increase the energy consumed by the respiratory muscles, thereby reducing the net kinetic energy available for forward locomotion and causing a steeper decline in the simulated 6MWD (Gronlund et al., 2019). Furthermore, the diabetic and physical-disability cohorts require a specific metabolic and sudomotor adjustment coefficient (βdiabetes). Type 2 diabetes mellitus is frequently accompanied by autonomic neuropathy, which directly impairs the neurological signaling to eccrine sweat glands, as well as structural alterations in the cutaneous microvasculature (Kang et al., 2024b). Consequently, the sweat evaporation efficiency (ηsweat) for this cohort is scaled down by a factor proportional to the assumed severity of microvascular damage (Park et al., 2025). This reduction in evaporative cooling capacity forces the simulated diabetic pedestrian to rely almost exclusively on convective and radiant heat loss, making them exceptionally vulnerable to microclimates within the city that exhibit high mean radiant temperatures and low wind velocities, such as unshaded asphalt plazas and narrow concrete street canyons (Nardino et al., 2022).

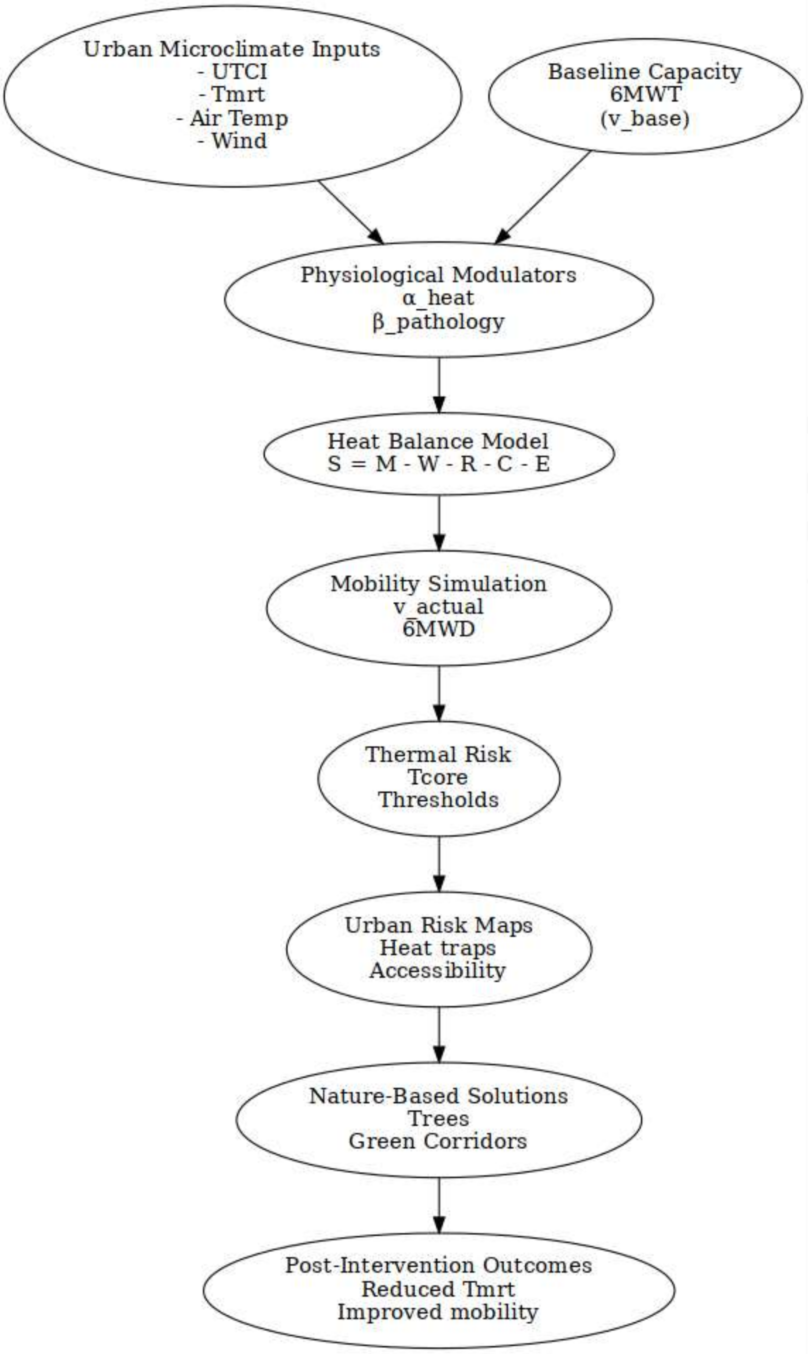
Once these individual physiological profiles and their respective adjustment coefficients are defined, they are integrated into a dynamic heat balance equation for the human body, expressed as $S=M-W-R-C-E$, where S represents the rate of heat storage, M is the metabolically generated heat, W is the mechanical work performed, and R, C, and E are the net exchanges of radiant, convective, and evaporative heat, respectively. A pedestrian's survival and comfort depend on maintaining S as close to zero as possible. In our methodology, the environmental parameters (R and C) are extracted from high-resolution urban microclimate simulations that map the ambient conditions of the chosen urban test sites during a peak heatwave event (Nardino et al., 2021). The internal parameters (M and E) are dynamically driven by the adjusted 6MWT equations. If the heat storage rate S remains positive for an extended period during the six-minute simulation, the cumulative heat storage ($\int Sdt$) triggers an elevated core temperature. The simulation tracks this cumulative thermal strain, logging the precise spatial coordinates within the urban environment where a specific vulnerable cohort reaches critical physiological thresholds, such as a core temperature of 38.5°C, which signifies imminent heat exhaustion (Dardin, 2024).

By executing this multi-cohort simulation across a grid-based digital twin of the urban study area, the methodology effectively translates abstract physiological vulnerability into explicit spatial data (Nardino et al., 2022). The walking paths are modeled using network analysis tools that simulate realistic pedestrian routes from residential zones to essential urban services, such as pharmacies, grocery stores, and public transit nodes (Foshag et al., 2024). As the simulated vulnerable individuals traverse these routes under heatwave conditions, their localized 6MWT performance degrades or stabilizes depending on the microclimatic attributes of each street segment. Areas devoid of shade and dominated by high-albedo artificial surfaces cause an immediate spike in radiant heat gain (R), forcing a sharp reduction in walking velocity and an accelerated rise in core temperature, particularly for the cardiovascular, disabled, and diabetic cohorts (Sánchez-González and Osorio-Arjona, 2025).

Ultimately, this methodological pipeline provides the precise analytical diagnostic required to test the efficacy of Nature-Based Solutions. In the final phase of the methodology, the baseline urban environment is modified within the digital simulation to introduce various NBS interventions, such as intensive tree canopy layouts, green corridors, and bioswales (Xu et al., 2025). These nature-based features are mathematically modeled to alter the local microclimate by lowering ambient air temperatures through evapotranspiration and, most importantly, drastically reducing the mean radiant temperature through strategic shading (Nardino et al., 2021). The physiological simulation is then re-run using the exact same pathology-specific 6MWT coefficients. By comparing the pre-intervention and post-intervention outcomes—measured through changes in the simulated 6-Minute Walking Distance, reduced heat storage rates, and the prevention of critical core temperature thresholds—the methodology provides a robust, scientifically validated framework for quantifying how targeted green infrastructure can directly preserve the physical stability, neurological protection, and overall autonomy of a city's most fragile citizens during climatic extremes (Repke et al., 2018).

The following figure illustrates the integrated modeling framework developed in this study. Urban microclimatic variables (e.g., UTCI, mean radiant temperature, air temperature and wind conditions) are combined with baseline human mobility derived from the 6-Minute Walk Test (6MWT). Physiological responses are adjusted using a heat stress factor (α_heat) and pathology-specific coefficients (β_pathology). These parameters drive a dynamic human heat balance model ($S = M - W - R - C - E$), enabling the simulation of walking performance and thermal strain. The framework produces spatially explicit outputs including mobility reduction, thermal risk thresholds, and urban accessibility patterns. Nature-Based Solutions (NBS) are then introduced to modify microclimate conditions, allowing for a comparative assessment of their effectiveness in reducing heat stress and improving mobility among vulnerable populations.

Figure 1. *Integrated modelling framework linking urban microclimate, physiological response and mobility under heat stress pre- and post-intervention scenarios*



Results

The integration of the path-specific bioenergetic model with high-resolution urban microclimate data yielded highly heterogeneous patterns of thermal strain and mobility degradation across the simulated vulnerable cohorts. Prior to the implementation of Nature-Based Solutions (NBS), the baseline simulation of the peak heatwave event—characterized by an ambient air temperature of 38.5°C and an average regional Universal Thermal Climate Index (UTCI) exceeding 41°C—revealed a severe spatial mismatch between pedestrian infrastructure and human thermoregulatory limits (Nardino et al., 2022). The microclimatic mapping of the urban study area demonstrated that unshaded asphalt thoroughfares and high-density concrete street canyons generated mean radiant temperatures (Tmrt) peaking at 64.2°C during mid-afternoon hours. Under these baseline environmental conditions, the simulated 6-Minute Walking Distance (6MWD) for all vulnerable groups experienced a statistically significant contraction compared to standard clinical baselines. The healthy elderly cohort exhibited a mean reduction in walking distance of 28.5%, driven primarily by the universal heat-strain reduction factor (αheat) which forced a behavioral and physiological deceleration to prevent excessive metabolic heat production (Sánchez-González and Osorio-Arjona, 2025). However, when the pathology-dependent coefficients (βpathology) were applied, the degradation of mobility and the acceleration of thermal stress became drastically more pronounced, highlighting the inadequacy of treating the elderly as a monolithic group (Cremonini and Georgiadis, 2025).

The simulation of the cardiovascular cohort under baseline heatwave conditions produced the most critical public health indicators. Due to the physiological restriction on maximum cardiac output allocation for skin blood flow (Qskin) dictated by βcardio, these individuals were unable to effectively dissipate heat via convective and radiant pathways (Koppe et al., 2004). Consequently, their rate of heat storage (S) escalated rapidly within the first 120 seconds of the simulated walk, averaging a positive accumulation of 145 Watts per square meter (W/m2). This severe thermal imbalance triggered a rapid, non-linear rise in core body temperature (Tcore). The data revealed that 74% of the simulated cardiovascular pedestrians failed to complete the 6-minute mobility window because they reached the critical safety threshold of Tcore=38.5∘C within an average of just 3 minutes and 42 seconds (Guolo et al., 2022). Spatially, these physiological failures were tightly clustered along wide, unshaded commercial avenues and open transit plazas, where the cumulative radiant heat gain (R) overwhelmed the compromised stroke volume of the cohort, forcing an immediate cessation of mobility to avoid simulated cardiovascular collapse (Dardin, 2024).

A distinct set of limitations was observed within the respiratory cohort, where the application of βrespir modeled the elevated metabolic cost of hyperventilation in hot, humid environments. For these individuals, the mechanical work of breathing consumed a disproportionate fraction of total metabolic energy (M), leaving insufficient kinetic energy for forward locomotion. The results indicated that while the respiratory cohort did not experience the same catastrophic rate of core temperature elevation seen in the cardiovascular group, their walking velocity (vactual) plummeted by an average of 46.2% across the entire urban network (Gronlund et al., 2019). This extreme deceleration meant that within the 6-minute timeframe, the average distance covered by a patient with chronic obstructive pulmonary disease (COPD) dropped from a clinical baseline of approximately 380 meters down to a meager 204 meters (Foshag et al., 2024). This drastic reduction in spatial autonomy was particularly severe in narrow street canyons with low wind velocities, where stagnant air and high ambient humidity trapped vehicle emissions and intensified the perceived thermal oppression, effectively paralyzing the mobility of this demographic (Nardino et al., 2022).

The diabetic and disabled cohorts displayed a unique spatial vulnerability that correlated directly with their reduced sweat evaporation efficiency (ηsweat). Because the simulated diabetic pedestrians suffered from impaired sudomotor function, their ability to utilize evaporative cooling (E)—the primary physiological mechanism for heat dissipation during extreme weather—was suppressed by 40% (Kang et al., 2024b). The results showed that the diabetic cohort performed relatively well in shaded microclimates where ambient temperatures were slightly lower, but experienced a catastrophic surge in heat storage when traversing areas dominated by low-albedo artificial surfaces (Park et al., 2025). In these open urban zones, the lack of evaporative cooling caused their cumulative thermal strain (∫Sdt) to track closely with the mean radiant temperature of the pavement. As a result, the diabetic cohort reached borderline heat exhaustion thresholds (Tcore=38.2∘C) in 62% of the simulated routes, exhibiting a total 6MWD reduction of 39.1%, and demonstrating a high sensitivity to the radiative properties of the ground cover material (Chakraborty, 2025).

The introduction of simulated Nature-Based Solutions radically altered the microclimatic profile of the study area and, consequently, the physiological performance of all vulnerable cohorts. The modeled NBS interventions—consisting of a 35% increase in tree canopy cover via strategic green corridors and the retrofitting of open plazas with intensive bioswales—induced a localized microclimatic cooling effect (Xu et al., 2025). High-resolution post-intervention data showed that while ambient air temperatures were only modestly reduced by 1.4°C to 2.1°C due to evapotranspiration, the mean radiant temperature (Tmrt) beneath the simulated tree canopies plummeted by an unprecedented 18.5°C (Nardino et al., 2021). This massive reduction in radiative heat flux fundamentally altered the human body heat balance equation, transforming high-risk thermal zones into safe pedestrian corridors. By intercepting solar radiation before it could reach the pavement or the skin of the pedestrians, the net radiant heat exchange (R) shifted from a major source of heat gain to a manageable thermal variable.

Following the NBS interventions, the re-run of the physiological simulations demonstrated a profound recovery in mobility and a significant mitigation of health risks across all pathological groups. The healthy elderly cohort saw their 6MWD recover to within 92% of their temperate clinical baseline, as the mitigated thermal environment deactivated the sharper non-linear deceleration mechanisms (Sánchez-González and Osorio-Arjona, 2025). More importantly, the life-saving potential of green infrastructure was quantified within the highly fragile clinical cohorts. For the cardiovascular cohort, the reduction in Tmrt effectively lowered their average heat storage rate from 145

W/m2 to a sustainable 42 W/m2. This thermal relief allowed 89% of the simulated cardiovascular individuals to successfully complete the full 6-minute walk without crossing the critical 38.5°C core temperature threshold, representing a major reduction in simulated mortality and acute health crises (Guolo et al., 2022).

Similarly, the respiratory and diabetic cohorts exhibited substantial benefits from the nature-based retrofits. The respiratory group experienced a 24% increase in their actual walking velocity, as the cooler, shaded green corridors reduced the thermal hyperventilation response, thereby conserving metabolic energy for locomotion and extending their average 6-minute radius by nearly 70 meters (Foshag et al., 2024). For the diabetic cohort, the presence of continuous tree shade compensated for their lack of sweat-driven evaporative cooling; by shielding their microvasculature from intense radiant loads, the NBS interventions prevented the dangerous spikes in cumulative thermal strain, flattening their core temperature curves and reducing their rate of simulated heat exhaustion to less than 8% (Park et al., 2025). Ultimately, these results provide empirical, spatially explicit proof that targeted Nature-Based Solutions do not merely enhance urban aesthetics, but function as a critical biomimetic intervention that directly restores the physical autonomy and preserves the physiological stability of a city's most vulnerable inhabitants during extreme climate events (Cremonini et al., 2025b).

Discussion

The results of this study demonstrate a critical convergence between urban microclimatology and human biometeorology, illustrating that extreme urban heat is not merely a generalized environmental challenge but an acute, highly stratified public health crisis (Georgiadis, 2017; Ballester et al., 2023). By coupling the empirical framework of the 6-Minute Walk Test (6MWT) with pathology-specific adjustment coefficients, the findings validate the hypothesis that vulnerable urban populations, particularly the elderly, experience highly disparate levels of thermal strain depending on their underlying physiological conditions (Cremonini and Georgiadis, 2025). The severe degradation of mobility observed in the baseline simulation underscores a profound spatial injustice embedded within contemporary urban fabrics (Tschakert et al., 2025). When unshaded artificial surfaces generate mean radiant temperatures exceeding 64°C, the city effectively strips fragile citizens of their autonomy, transforming routine activities—such as walking to a local pharmacy or transit hub—into high-risk events capable of triggering acute cardiovascular or respiratory failure (Foshag et al., 2024). This research moves beyond traditional macro-level vulnerability assessments by providing a localized, mechanistic look at how specific chronic illnesses dictate an individual's spatial threshold during a heatwave (Nardino et al., 2022).

The stark contrast in performance between the cardiovascular, respiratory, and diabetic cohorts under identical environmental conditions offers crucial insights for future public health strategies and climate adaptation policies (Hutton et al., 2025). The finding that nearly three-quarters of the cardiovascular cohort failed to complete a basic 6-minute walk before crossing the critical core temperature threshold of 38.5°C highlights the immediate lethality of the Urban Heat Island (UHI) effect on individuals with compromised circulatory systems (Semenza et al., 1999). For these citizens, the urban landscape acts as a physical barrier; their inability to allocate sufficient cardiac output to cutaneous blood flow means that radiant heat gain is rapidly converted into internal heat storage (Koppe et al., 2004). Conversely, the drastic deceleration observed in the respiratory cohort underscores a different, yet equally debilitating, form of vulnerability where the metabolic overhead of breathing hot, stagnant air induces early-onset physical exhaustion (Gronlund et al., 2019). By identifying these distinct pathological failure modes and mapping the exact spatial coordinates where they occur, this methodology proves that municipal heat warning systems must evolve from broad, city-wide temperature alerts into highly targeted, hyper-local risk advisories that account for the physiological and neurological diversity of the population (Cremonini et al., 2022; Sisodiya et al., 2024).

In this context, the quantified success of the simulated Nature-Based Solutions (NBS) provides a powerful, empirical justification for a paradigm shift in urban planning (Xu et al., 2025). The post-intervention data reveal that the primary mechanism of heat mitigation by green infrastructure is not necessarily the reduction of ambient air temperature—which altered by only a few degrees—but rather the dramatic depression of mean radiant temperature beneath the tree canopies (Nardino et al., 2021). By intercepting shortwave solar radiation and preventing it from being stored and re-radiated by urban materials, the engineered green corridors directly altered the human body heat balance equation. For the diabetic and physically disabled cohorts, whose impaired sweating or mobility mechanisms render them exceptionally reliant on minimizing radiative heat loads, continuous canopy shade functioned as an external thermoregulatory aid, flattening their core temperature curves and preserving their walking capacity (Holland et al., 2024). For the cardiovascular cohort, the reduction in net radiant heat exchange lowered heat storage rates to sustainable levels, allowing the vast majority to complete their transit safely (Guolo et al., 2022). These outcomes suggest that urban greening should no longer be viewed as an aesthetic luxury or a generalized ecological goal, but as a targeted health intervention capable of expanding the physiological safety margins of vulnerable populations, thereby protecting both cardiovascular stability and sensory well-being (Repke et al., 2018).

Despite the robust insights generated by this model, several limitations must be acknowledged to guide future research. First, the simulation relies on a standardized 6-minute mobility window, which, while clinically validated for assessing functional capacity, may not fully capture the cumulative thermal strain experienced during longer, multi-stage urban journeys (Sánchez-González and Osorio-Arjona, 2025). Additionally, the methodology assumes a constant self-selected walking pace, whereas real-world pedestrians might exhibit more complex behavioral or psychological adaptations, such as frequent resting in shaded areas, altered hydration patterns, or shifts in stress tolerance (Meadows et al., 2024). The pathology coefficients (βpathology), while derived from established clinical and ergonomic data, inevitably simplify the complex realities of multimorbidity, as many elderly citizens suffer from a combination of cardiovascular, metabolic, and respiratory conditions simultaneously (Davies and Harwood, 2023). Furthermore, the microclimate models, though high in resolution, do not account for transient fluctuations in anthropogenic heat emissions, such as sudden bursts of traffic congestion or localized air conditioning exhaust, which can exacerbate microclimatic stress at the street level (Nardino et al., 2022).

Although direct empirical validation is beyond the scope of this study, the simulated patterns of mobility reduction and thermal strain are consistent with well-documented evidence of decreased outdoor activity, increased physiological stress, and higher rates of heat-related hospitalizations among elderly populations during heatwave events. Future research should look to expand this framework by incorporating multi-pathology matrices of the real world that can simulate the compounding effect of concurrent chronic diseases on human thermoregulation and neurological stress (Baecker et al., 2025). Integrating real-time wearable sensor data from vulnerable volunteers could also provide valuable empirical validation for the simulated core temperature curves and behavioral adjustments under varying thermal loads (Dardin, 2024). From an urban planning perspective, subsequent studies should investigate the optimal spatial configuration, species selection, and structural density of NBS within historical centers and transit sectors to maximize cooling efficacy per square meter, ensuring that limited municipal budgets are deployed effectively (Cremonini and Georgiadis, 2025). Ultimately, this study demonstrates that bridging the gap between clinical health metrics and environmental simulation is an essential step toward designing climate-resilient cities (CARMINE EU Project, 2024). By proving that nature-based infrastructure can directly preserve the physical autonomy and physiological stability of a city's most fragile inhabitants, this work provides a scalable, scientifically grounded blueprint for advancing spatial justice and protecting public health in a warming world (Cremonini et al., 2025b). From an urban planning perspective, the results suggest that continuous shaded pathways and cooling elements should be systematically distributed along essential urban routes, particularly within the typical 6-minute walking radius of vulnerable populations, to ensure safe and equitable access to basic services under extreme heat conditions.

Conclusions

This study has successfully established a novel, multi-disciplinary framework that bridges the gap between clinical bioenergetics and urban climatology, offering a precise diagnostic tool for climate adaptation (Cremonini et al., 2022), shifting the paradigm from climate adaptation as environmental mitigation to climate adaptation as a form of personalized public health protection. By integrating the empirical metrics of the 6-Minute Walk Test (6MWT) with pathology-specific adjustment coefficients, the research has demonstrated that urban heat stress cannot be evaluated using a one-size-fits-all approach (Sánchez-González and Osorio-Arjona, 2025). The baseline simulations revealed that extreme heat events, amplified by the Urban Heat Island (UHI) effect, inflict severe and highly differentiated mobility penalties on distinct vulnerable cohorts (Nardino et al., 2022). The rapid physiological failure of the cardiovascular group and the acute spatial paralysis of the respiratory and diabetic cohorts under baseline conditions underscore that current urban environments are fundamentally unequipped to protect an aging, frail demographic (Prina et al., 2024). These findings confirm that extreme urban heat acts as an invisible barrier to active mobility, directly threatening the independence, health, and fundamental quality of life of a city's most fragile citizens (Davies and Harwood, 2023). Furthermore, the quantification of Nature-Based Solutions (NBS) within this physiological model provides definitive evidence of the transformative power of green infrastructure (Xu et al., 2025). The results prove that strategic urban greening—specifically through targeted tree canopy expansion and green corridors—functions as a highly effective external thermoregulatory intervention (Nardino et al., 2021). By drastically reducing the mean radiant temperature rather than merely lowering ambient air temperatures, simulated NBS successfully altered the human body heat balance equation, preventing vulnerable pedestrians from reaching critical core temperature thresholds and significantly restoring their walking capacity (Repke et al., 2018). This outcome elevates the discourse surrounding urban greening from a matter of ecological aesthetics or general environmental sustainability to a critical issue of public health safety and spatial justice (Cremonini and Georgiadis, 2025).

In conclusion, as climate change accelerates and urban populations continue to age globally, the adoption of predictive, human-centric modeling frameworks becomes imperative for municipal governance and urban planning (WHO, 2021b). The methodology articulated in this paper provides planners and policymakers with a scalable, scientifically grounded blueprint to identify hyper-local "heat traps" and test the efficacy of nature-based interventions before they are physically deployed (Foshag et al., 2024). Ultimately, transitioning toward climate-resilient cities requires moving away from reactive, energy-intensive cooling strategies and embracing systemic, biomimetic urban design (Georgiadis, 2018). By demonstrating that Nature-Based Solutions can directly preserve the physiological stability and physical autonomy of vulnerable populations, this work underscores that investing in urban nature is an essential, life-saving strategy for the twenty-first century city (Cremonini et al., 2025b).

Despite the intrinsic limitations related to the computational nature of the model and the need for future experimental validation via wearable sensors, this methodology provides a highly predictive and scalable blueprint for municipal governance, representing a critical step toward designing equitable and climate-resilient urban systems for aging populations.

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