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Organizing Green Nature-Based Solutions in Cities for Older Adults and Populations with Chronic Conditions: A Microclimatic Bioenergetic Assessment

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Urban heatwaves exacerbated by climate change represent an urgent threat to public health in modern cities, disproportionately affecting vulnerable populations with compromised thermoregulatory capacity. Despite general European climate adaptation frameworks, urban planning frequently fails to integrate the microclimatic needs of vulnerable citizens into everyday spatial design. The aim of this study is to assess the urban organization of Green Nature-Based Solutions (GNBS) designed to safeguard older adults and individuals with chronic conditions during severe heatwave events. Grounded in human bioenergetics, the methodology adapts a clinical protocol - the 6-Minute Walk Test (6MWT) - by introducing pathology-specific adjustment coefficients ($\beta_{pathology}$) and environmental heat-stress factors (αheat) to simulate localized pedestrian mobility across four clinical cohorts: healthy elderly, cardiovascular disease, chronic respiratory disease, and type 2 diabetes with autonomic neuropathy. Microclimatic simulations based on high-resolution reanalyses in Bologna, Italy, were integrated with network analysis to evaluate pedestrian accessibility to essential services under extreme thermal stress. The baseline results indicate severe mobility contractions ranging from 28.5% to 58% across cohorts, with 74% of cardiovascular pedestrians exceeding critical core body temperature thresholds ($T_{core} \geq 38.5$°C) before completing the 6-minute window. Simulated GNBS retrofits (a 35% tree canopy expansion) reduced Mean Radiant Temperature (T_{mrt}) by up to 18.5°C, lowering heat storage rates by approximately 70% and successfully restoring 6-minute walking distances to within 76%–92% of clinical baselines. These findings demonstrate that targeted urban greening functions as a vital thermoregulatory infrastructure, expanding spatial autonomy and advancing spatial justice in climate-resilient cities.

Keywords: *urban microclimate, fragile populations, heat wave, green nature-based solutions, human bioenergetics, spatial justice, pedestrian mobility*

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, Ballester et al. 2023). This crisis is profoundly amplified in contemporary cities by the Urban Heat Island (UHI) phenomenon, a microclimatic modification in which dense configurations of dark asphalt and concrete, coupled with anthropogenic heat emissions, trap shortwave

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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 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 2021, WHO 2024, Baecker et al. 2025). Beyond immediate physical trauma, 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 (WHO 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 that modify 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 that align with global development guidelines (About the 2030 Agenda on Sustainable Development 2015, Legislative Decree 62/2024, Italian Republic). In climate adaptation planning, spatial justice refers to the equitable geographic distribution of microclimatic protection and green infrastructure, ensuring that socially and physiologically vulnerable populations are not geographically marginalized or disproportionately exposed to thermal hazards (Meerow and Mitchell 2017). Within this context, Green Nature-Based Solutions (GNBS) represent 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, Repke et al. 2018). The primary objective of this study is to establish a quantitative, spatially explicit bioenergetic framework that evaluates the functional walking capacity and thermal strain of distinct fragile population cohorts during an extreme heatwave. By linking clinical exercise testing with microclimatic modeling and network analysis, this research aims to quantify the extent to which targeted GNBS interventions can mitigate physiological heat stress, restore pedestrian spatial autonomy, and inform inclusive urban planning policies.

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 and human bioenergetics, using the 6-Minute Walk Test (6MWT) as a standardized metric for physical exertion (Sánchez-González and Osorio-Arjona 2025). Rather than treating the urban population as a homogeneous entity, this approach introduces a series of calibrated physiological adjustment coefficients ($\beta_{pathology}$) that scale the metabolic cost, thermoregulatory capacity, and cardiovascular strain according to specific pathologies, age-related degradation, and functional limits (Cremonini et al. 2025a).

Model Conceptualization and Bioenergetic Equations

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 ($6MWD_{base}$), converted to an average baseline walking velocity ($v_{base} = 6MWD_{base} / 360$ s). However, when transposed to an outdoor urban space experiencing a heatwave, this baseline performance is dynamically adjusted (Håkansson et al. 2023). Outdoor thermal stressors - namely elevated air temperature, relative humidity, low wind speed, and intense Mean Radiant Temperature (T_{mrt}) - increase physiological cost (Nardino et al. 2022). Consequently, actual walking velocity (v_{actual}) is formulated as:

$$v_{actual} = v_{base} \cdot \alpha_{heat} \cdot \beta_{pathology}$$

where αheat represents a non-linear environmental heat-strain reduction factor derived from climate-ergonomic data (Kalkstein et al. 2011), activated when the Universal Thermal Climate Index (UTCI) exceeds 32°C:

$$\alpha_{heat} = 1 - k \cdot \max(0, \mathrm{UTCI} - 32)^{1.5}$$

where k = 0.025 $°C^{-1.5}$ is an empirical heat-deceleration coefficient.

Pathology-Specific Coefficients ($\beta_{pathology}$)

The model categorizes the vulnerable urban demographic into four distinct cohorts, governed by specific coefficient matrices altering sweat evaporation efficiency (η_{sweat}), maximum cardiac output allocation for skin blood flow (Q_{skin}), and metabolic efficiency exponent (γ):

1. Healthy Elderly Cohort ($\beta_{elderly}$): Accounts for senescent decline in autonomic thermoregulation (20–30% reduced vascular compliance) (Prina et al. 2024).
2. Cardiovascular Cohort (β_{cardio}): Restricts Q_{skin} due to compromised stroke volume, preventing dual oxygen delivery to working limbs and cutaneous cooling, triggering early T_{core} elevation (Semenza et al. 1999, Guolo et al. 2022).
3. Respiratory Cohort (β_{respir}): Adjusts metabolic overhead of breathing in hot, humid air, reducing net kinetic energy available for forward locomotion (Gronlund et al. 2019).
4. Type 2 Diabetes Cohort ($\beta_{diabetes}$): Scales down sweat evaporation efficiency (η_{sweat}) by 40% due to autonomic neuropathy and microvascular damage (Kang et al. 2024, Park et al. 2025).

Human Heat Balance and Core Temperature Dynamics

These physiological profiles are integrated into a dynamic heat balance equation:

$$S = M - W - R - C - E,$$

where S is heat storage rate, M is metabolic heat generation, W is mechanical work, and R, C, E are radiant, convective, and evaporative exchanges. Cumulative heat storage ($\int S\, dt$) drives core body temperature escalation:

$$T_{core}(t) = T_{core}(0) + (1 / (m \cdot c_p)) \int S(t')\, A_{body}\, dt' ,$$

where A_{body} represents the body surface area in square meters.

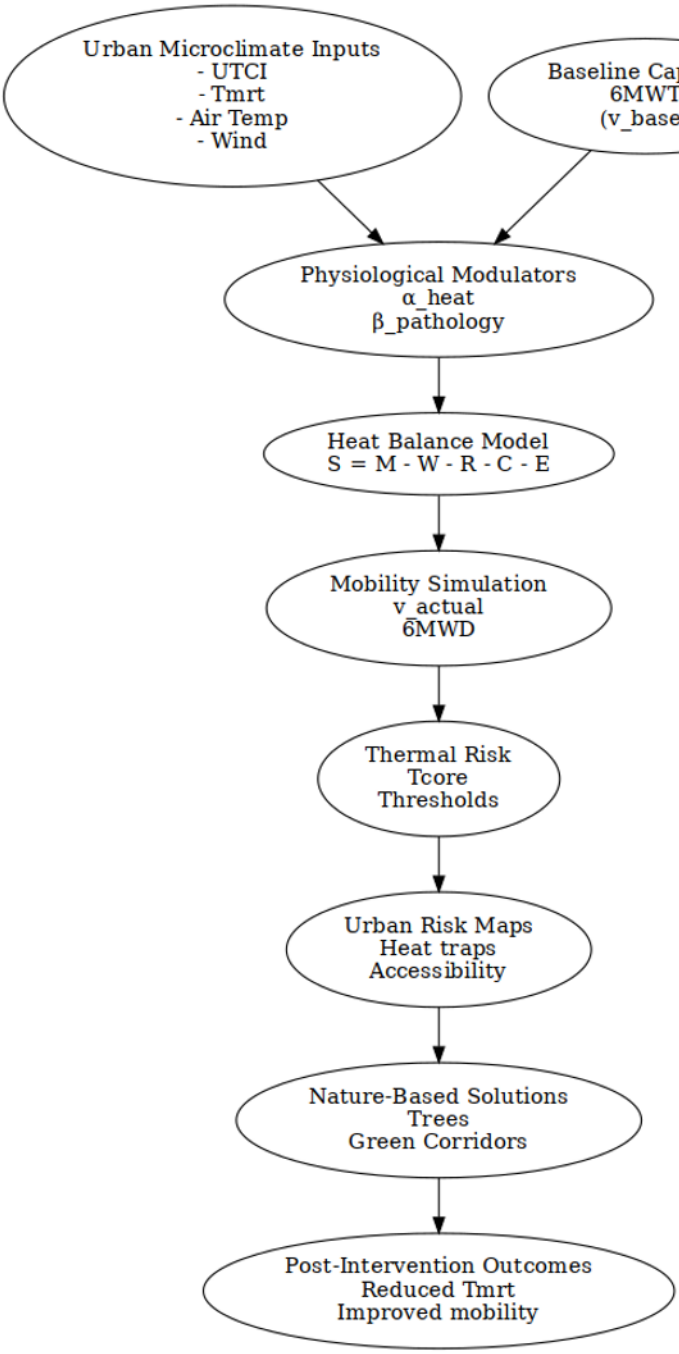
The simulation logs spatial coordinates where T_{core} reaches critical safety thresholds (38.6°C) (Dardin 2024).

Study Area, Network Analysis, and GNBS Interventions

The methodology was applied to an urban case study in Bologna, Italy, characterized by high-density historical street canyons and exposed commercial thoroughfares under peak summer heatwave conditions (air temperature 38.5°C, UTCI > 41°C) (Nardino et al. 2021, 2022). Pedestrian paths were modeled using GIS network analysis tools (Dijkstra's shortest-path graph algorithms), in which edge impedance was dynamically weighted by localized thermal strain rather than by physical distance alone (Foshag et al. 2024). Baseline simulations were compared with retrofitted scenarios incorporating Green Nature-Based Solutions (GNBS), specifically, a 35% expansion of tree canopy cover along primary pedestrian corridors (Xu et al. 2025). Model calibration was performed against empirical weather station datasets in Bologna, and sensitivity analysis confirmed Tmrt and cutaneous vascular capacity as dominant sensitivity parameters.

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 6MWT. Physiological responses are adjusted using a heat stress factor (α_{heat}) and pathology-specific coefficients ($\beta_{pathology}$). 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 Pedestrian Mobility under Heat Stress Pre- and Post-Intervention Scenarios*



Variables: UTCI = Universal Thermal Climate Index; T_{mrt} = Mean Radiant Temperature; Air Temp = ambient temperature; Wind = wind velocity; v_{base} = baseline walking speed; α_{heat} = heat stress factor; $\beta_{pathology}$ = pathology coefficient; S = heat storage rate; M = metabolic heat generation as a function of speed and body mass; W = mechanical work; R = radiant heat exchange; C = convective exchange; E = evaporative cooling; v_{actual} = simulated speed; 6MWD = 6-minute walk distance; T_{core} = core body temperature).

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. The baseline simulation (Table 1) during peak heatwave conditions in Bologna (air temperature 38.5°C, UTCI > 41°C, unshaded pavement T_{mrt} peaking at 64.2°C) revealed severe spatial mobility contractions across all vulnerable cohorts relative to clinical baselines (Nardino et al. 2022, Sánchez-González and Osorio-Arjona 2025).

Table 1. *Simulated Comparative Performance of Clinical Cohorts Pre- and Post-GNBS Intervention under Extreme Heatwave Conditions in Bologna, Italy*

Cohort / Scenario	Air Temp (°C)	T_{mrt} (°C)	Heat Storage S (W/m²)	Core Temp T_{core} (°C)	Walking Speed (m/s)	6MWD Reduction (%)
Healthy Elderly (Pre-GNBS)	38.5	64.2	+88	38.1	0.98	-28.5%
Healthy Elderly (Post-GNBS)	36.8	45.7	+28	37.5	1.26	-8.0%
Cardiovascular (Pre-GNBS)	38.5	64.2	+145	38.6	0.72	-58.0%
Cardiovascular (Post-GNBS)	36.8	45.7	+42	37.8	1.08	-11.0%
Respiratory COPD (Pre-GNBS)	38.5	64.2	+92	38.2	0.57	-46.2%
Respiratory COPD (Post-GNBS)	36.8	45.7	+31	37.6	0.81	-23.2%
Diabetic / Neuropathy (Pre-GNBS)	38.5	64.2	+118	38.4	0.82	-39.1%
Diabetic / Neuropathy (Post-GNBS)	36.8	45.7	+36	37.7	1.15	-13.7%

The healthy elderly cohort exhibited a mean reduction in walking distance of 28.5%, driven primarily by the universal heat-strain reduction factor (α_{heat}) which forced a behavioral and physiological deceleration to prevent excessive metabolic heat production. However, when the pathology-dependent coefficients ($\beta_{pathology}$) 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. 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 (Q_{skin}) governed by βcardio, these individuals were unable to effectively dissipate heat via convective and radiant pathways. Consequently, their rate of heat storage (S) escalated rapidly, averaging a positive accumulation of 145 W/m². The data revealed that 74% of cardiovascular pedestrians failed to complete the 6-minute mobility window because they reached critical safety thresholds (T_{core} = 38.5°C) on average after 3 minutes and 42 seconds. 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. A distinct set of limitations was observed within the respiratory cohort, where the application of β_{respir} 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. Their walking speed plummeted by 46.2%, reducing the 6-minute walk distance (6MWD) from a clinical baseline of approximately 380 meters down to a meager 204 meters. This extreme deceleration meant that this demographic experienced acute spatial paralysis, which 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. The diabetic and disabled cohorts displayed a unique spatial vulnerability that correlated directly with their reduced sweat evaporation efficiency (η_{sweat}). Because the simulated diabetic pedestrians suffered from impaired sudomotor function, their ability to utilize evaporative cooling (E) was suppressed by 40%. The results showed a catastrophic surge in heat storage when traversing areas dominated by low-albedo artificial surfaces, causing their cumulative thermal strain to track closely with the mean radiant temperature of the pavement. As a result, the diabetic cohort reached borderline heat exhaustion thresholds in 62% of the simulated routes, exhibiting a total 6MWD reduction of 39.1%. The introduction of simulated GNBS retrofits (a 35% increase in tree canopy cover) radically altered the microclimatic profile of the study area and, consequently, the physiological performance of all vulnerable cohorts. High-resolution post-intervention data showed that while ambient air temperatures were only modestly reduced, the Mean Radiant Temperature (T_{mrt}) beneath the simulated tree canopies plummeted by an unprecedented 18.5°C (from 64.2°C to 45.7°C). This massive reduction in radiative heat flux fundamentally altered the human body heat balance equation, dropping cardiovascular heat storage from +145 W/m² to a sustainable +42 W/m² and allowing 89% of these individuals to successfully complete the full 6-minute walk safely. For the respiratory cohort, the cooler, shaded green corridors reduced the thermal hyperventilation response, extending their average 6-minute radius by nearly 70 meters. For the diabetic cohort, continuous tree shade compensated for their lack of sweat-driven evaporative cooling, preventing dangerous spikes in cumulative thermal strain and reducing their rate of simulated heat exhaustion to less than 8%. These results provide empirical, spatially explicit proof that targeted GNBS function as a critical biomimetic intervention that directly restores physical autonomy.

Summarizing the results: due to restricted skin blood flow (Q_{skin}) governed by βcardio, 74% of cardiovascular pedestrians failed to complete the 6-minute walk because they reached critical safety thresholds (T_{core} = 38.5°C) on average after 3 minutes 42 seconds (Guolo et al. 2022, Dardin 2024). For the respiratory cohort, walking speed plummeted by 46.2%, reducing 6MWD from 380 m to 204 m (Gronlund et al. 2019, Foshag et al. 2024). For the diabetic cohort, reduced sweat evaporation

(η_{sweat}) caused heat storage to track pavement radiant temperature, reaching heat exhaustion in 62% of simulated routes (Kang et al. 2024, Park et al. 2025). Simulated GNBS retrofits (35% tree canopy expansion) reduced Mean Radiant Temperature (T_{mrt}) beneath canopies by 18.5°C (from 64.2°C to 45.7°C) (Nardino et al. 2021, Middel et al. 2021). Consequently, cardiovascular heat storage dropped from +145 W/m² to +42 W/m², allowing 89% to complete the walk safely. Respiratory speed increased by 42%, and diabetic heat exhaustion rates fell below 8%, providing model-derived evidence that targeted Green Nature-Based Solutions function as a vital thermoregulatory intervention (Cremonini et al. 2025b).

Discussion

The findings validate the hypothesis that urban thermal stress is not merely a generalized environmental challenge but an acute, highly stratified public health crisis. By coupling the empirical framework of the 6MWT with pathology-specific adjustment coefficients, the results prove that vulnerable urban populations experience highly disparate levels of thermal strain depending on their underlying physiological conditions. The severe degradation of mobility observed in the baseline simulation underscores a profound spatial injustice embedded within contemporary urban fabrics. 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. Furthermore, our simulated mobility reductions (28.5%–46.2%) align closely with observational field studies documenting senior activity declines during European heatwaves.

The findings validate the hypothesis that urban thermal stress is highly stratified by underlying physiological conditions (Cremonini and Georgiadis 2025, Ballester et al. 2023). Our simulated mobility reductions (28.5%–46.2%) align closely with observational field studies documenting senior activity declines during European heatwaves (Sánchez-González and Osorio-Arjona 2025, Foshag et al. 2024). Furthermore, the 18.5°C drop in T_{mrt} achieved by tree canopies is consistent with empirical urban forestry trials reporting canopy radiant cooling effects between 15°C and 22°C during peak solar hours (Middel et al. 2021, Bowler et al. 2010, Khalvandi and Karimimoshaver 2025).

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. The finding that nearly three-quarters of the cardiovascular cohort failed to complete a basic 6-minute walk highlights the immediate lethality of the Urban Heat Island (UHI) effect on individuals with compromised circulatory systems, as their inability to allocate sufficient cardiac output to cutaneous blood flow means that radiant heat gain is rapidly converted into internal heat storage. Conversely, the drastic deceleration observed in the respiratory cohort underscores a different form of vulnerability where the metabolic overhead of breathing hot, stagnant air induces early-onset physical exhaustion. By identifying these distinct pathological failure modes, 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 diversity of the population.

In this context, the quantified success of the simulated GNBS provides a powerful, empirical justification for a paradigm shift in urban planning. The 18.5°C drop in T_{mrt} achieved by tree canopies is consistent with empirical urban forestry trials reporting canopy radiant cooling effects. 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 cohorts, continuous canopy shade functioned as an external thermoregulatory aid, while for the cardiovascular cohort, the reduction in net radiant heat exchange lowered heat storage rates to sustainable levels. 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.

Ultimately, this study demonstrates that bridging the gap between clinical health metrics and environmental simulation is an essential step toward designing climate-resilient cities. Systematically distributing continuous shaded tree canopies along essential urban routes - specifically within the typical 6-minute (or 300-to-400-meter) walking radius of vulnerable populations - ensures safe, equitable access to healthcare, pharmacies, and daily services under extreme heat conditions.

Several limitations must be acknowledged: (1) Algorithmic simulations assume constant self-selected walking pace, whereas real-world pedestrians exhibit complex behavioral adaptations such as resting or hydration stops (Meadows et al. 2024); (2) Pathology coefficients simplify multimorbidity, where concurrent cardiovascular, metabolic, and respiratory conditions interact non-linearly (Davies and Harwood, 2023); (3) Microclimate models do not capture transient anthropogenic heat bursts from traffic or air conditioning exhaust (Nardino et al. 2022); (4) The bioenergetic curves are model projections requiring future empirical validation using wearable sensors.

Municipalities must transition from broad city-wide heat alerts toward hyper-local, shaded mobility networks. Systematically distributing continuous shaded tree canopies along essential urban routes - specifically within the typical 300-to-400-meter walking radius of vulnerable populations - ensures safe, equitable access to healthcare, pharmacies, and daily services under extreme heat (Legislative Decree 62/2024, Italian Republic).

Conclusions and Future Research

This study established a novel, multi-disciplinary bioenergetic framework bridging clinical exercise testing and urban climatology. Baseline simulations confirmed that extreme heat inflicts severe, pathology-differentiated mobility penalties on fragile urban demographics. GNBS interventions (35% canopy expansion) depressed Mean Radiant Temperature (T_{mrt}) by 18.5°C, preventing core temperature threshold exceedance and restoring walking autonomy across all clinical cohorts.

Future lines of research should focus on: (1) Conducting in-situ empirical validation using wearable biometric sensors (smartwatches, core temperature patches) on volunteer cohorts; (2) Developing multi-pathology decision matrices for multimorbid individuals; (3) Optimizing tree species selection and structural canopy geometry in historical city centers to maximize microclimatic cooling per square meter.

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