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Special Issue 2.2025

Climate crisis and spatial planning

Green infrastructure and supply of ecosystem services

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The cover image: The pedestrian route of Via Chiaia in the City of Naples by TeMA Editorial Staff

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Reducing UHI in historical centres: the greening transformation of open small spaces in San Lorenzo district in the city of Naples (Italy)

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Abstract
Urban Heat Island effects intensify thermal discomfort and energy consumption in densely built areas, particularly in historical city centres characterised by compact and stratified urban fabric. Such conditions necessitate targeted greening interventions in these urban fabrics, which are the focus of this study on the San Lorenzo district in Naples, a representative Mediterranean historic city, where limited open spaces coexist with strict heritage conservation constraints. Utilising ENVI-met 5.7 simulations, the research models microclimatic conditions under current and greening scenarios, considering detailed urban morphology, vegetation types, and local climate data representative of peak summer days. Physiological Equivalent Temperature, Mean Radiant Temperature and Universal Thermal Comfort indices are employed to measure thermal comfort improvements through targeted greening interventions in small yet strategically significant spaces like inner cohorts of historical buildings. The findings demonstrate the cooling potential of integrating green transformation also in the small inner courtyards of the noble buildings by restoring the original function of these spaces as gardens and orange groves. This kind of solution can be efficiently adopted for a sustainable urban planning, helping mitigate UHI impacts and improve residents' well-being amidst global warming challenges.

Keywords
Urban open spaces; UHI; Courtyards; ENVImet; Urban greening

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1. Introduction

Global warming determined by climate change, intensifies heat stress hazards in urban areas, threatening people's health (especially fragile ones like children, elderly and low-income) and the regenerative capacities of vegetated and permeable surfaces (Nita et al., 2022). IPCC data show that the global average surface temperature was 0.99 °C higher than the preindustrial period, as measured between 2001 and 2020 (Lee et al., 2024). Furthermore, the expected worldwide temperature rise by the end of this century is now estimated to be 2.7°C, rather than 2.2°C (Lee et al., 2024), due to the slow and still widespread unwillingness to implement concrete strategies and actions to reduce climate-altering emissions. The consequent heat waves risk seriously to be further long, intense and frequent, leading to an increase in illness and mortality, as already happened in the period 2019-2022 compared to the beginning of the 2000s: 72% vs 30% (WMO, 2024).

In Europe, the worst scenario of severe heat waves is expected to occur in the Mediterranean countries, especially the Southern ones that are characterised by highly dense built-up and populated urban areas (EEA, 2024).

In this context of heat risk, the Urban Heat Island (UHI) phenomenon, combined with an extreme heat climate, is expected to worsen by creating a negative feedback loop. On one hand, higher temperatures and the associated thermal discomfort experienced by people lead to an increased demand for air conditioning, resulting in greater energy consumption, elevated outdoor temperatures, and higher greenhouse gas (GHG) emissions. On the other hand, vegetated and permeable surfaces within built-up areas are subjected to increased heat stress, along with the related air pollutants emitted into the atmosphere (Yi et al., 2025). Furthermore, from a broader systemic perspective, it is important to note that these microclimatic dynamics within and around urban areas contribute to escalating anthropogenic pressure on the soil, which is already severely threatened by the sealing process. This results in a reduction in the interception, storage, and infiltration of rainwater, thereby intensifying the climate vulnerability of cities (Guida, 2021; Gargiulo & Zucaro, 2025).

Therefore, the knowledge and the measurement of the relationships between the built environment features and UHI are relevant to define effective measures and solutions to improve the resilience of cities. Scholars like Bardhan et al. (2020), Hong et al. (2020), Deng et al. (2024) develop methods based on building energy and thermal simulation tools to simulate the radiative exchanges and fluxes among the different urban physical elements and assess the positive impact of cooling surfaces, with particular attention to the greening ones. The release of water vapour from plants induces the humidity increase with the increase of air reflection of solar radiation and final temperature decrease, and these positive and synergic benefits can be obtained by greening the city from the building level (cool and green roofs) to the district and urban one (open spaces and streets) concurrently (EEA, 2024; Lee et al., 2024; Cutini & Mara, 2025). However, the most advocated solution of localising vegetated surfaces within urban systems is hindered by two main obstacles:

- the amount of spaces (places and streets) that can be suitable for the greening transformation is limited in urban highly built-up cities and this presence is even more limited in their historical centres due to the building density, the stringent regulatory constraints and limits to transformations whose purpose is to protect and enhance historical-architectural-cultural heritage (peculiar to stratified urban contexts) and which are therefore incompatible with the needs of adaptation to climate change;
- the limited ability to develop a resilient urban project aimed at providing target-based greenery interventions integrated among them, according to the different physical (e.g. fabric type), functional (e.g. service offerings), socio-economic (e.g. needs of the prevailing segments of the population) and micro-climatic (air and soil temperature, etc.) characteristics of each part of the city.

The second aspect turns out to be particularly true for the Italian context, where the high number of climate adaptation and sustainable energy action plans is contrasted with an increase in green areas that is negligible in the last 10 years (Varbova, 2022) and inadequate compared to both the European and beyond European context, those further afield such as Medellin in Colombia and New York in the United States (Ascione et al., 2026; Gargiulo et al., 2017; Stiuso, 2025).

The historic centre of a city, especially if it is a layered city such as those found in the Mediterranean basin, constitutes a large part of the area where average temperatures are higher due to intrinsic physical characteristics that lead to high heat peaks (Donateo et al., 2023; Giannaros & Melas, 2012). The widespread use of highly emissive materials such as asphalt or stone paving, the geometry and orientation of road axes that can hinder natural ventilation, high building density and the (almost) total absence of vegetation and trees are among the main factors that accentuate the UHI phenomenon and therefore the severe thermal discomfort of those who live in and use this part of the city, both during the day and at night, given that the heat accumulated during the daytime remains trapped even after solar radiation due to the high emissivity of the surfaces present (Ahmed et al., 2024; Hu et al., 2023).

In historic centres, such as in the emblematic case of Naples, the fabric is characterised by a strong physical and functional stratification, which leaves limited open spaces available, often residual in relation to the building process. These open spaces are mainly constituted by small squares or internal courtyards, which are the only areas available for UHI mitigation measures (Gargiulo & Zucaro, 2023).

Fig.1 Typical green courtyard in the historical centre of the city of Naples

The limited availability of green areas, combined with the compact and consolidated layout of the historic centre, makes mitigation measures particularly challenging. Added to this are stringent urban planning restrictions aimed at preserving the cultural, architectural and identity value of these parts of the city. These constraints severely limit the possibilities for transforming and renovating open spaces, thus requiring careful and innovative consideration of the methods of intervention, which must reconcile climate effectiveness, respect for heritage and urban usability.

Therefore, rising temperatures require the ability to transform and reorganise urban spaces and activities to ensure both resilience to the unexpected effects of climate change and the preservation of urban assets and, above all, an improvement in people's quality of life.

With this in mind, the work, which focuses on historic city neighbourhoods with the highest building densities, proposes an experiment aimed at greening open spaces, such as the courtyards of noble buildings, or squares and open spaces, to measure the possible benefits in terms of lowering the perceived temperature. The conversion of built-up areas within historic neighbourhoods into permeable, tree-lined spaces could be an effective measure both for reducing the impact of the UHI and for enhancing historic city centres. In fact, in many cases, converting them back to their original function as gardens and vegetable plots, in direct contact with residences, could improve the microclimate, encourage social interaction and increase the attractiveness and liveability of historic centres (Diz-Mellado et al., 2021, 2023). Most of these spaces are currently used as private parking areas and, as such, are difficult to convert into green spaces due to the very high demand for parking spaces. To overcome the constraint of high private parking demand, a staged redevelopment approach can be adopted, as a portion of existing parking areas can be repurposed for greening during off-peak hours or in coordination with local urban mobility initiatives (e.g., pedestrian zones) ensuring continuity of access while gradually increasing green coverage.

The cooling thermal benefits and the lower perceived temperature obtained by greening the widespread open spaces and turning back to gardens the courtyards of buildings in a historical district of the city of Naples (in the South of Italy) are measured through the micro-climate simulation tool ENVI-met providing Physiological Equivalent Temperature (PET), Mean Radiant Temperature (MRT) and and Universal Thermal Comfort Index (UTCI) output parameters. By applying these interventions, this study seeks to deliver practical design guidance to enhance the thermal comfort and sustainability of these spaces, delivering useful findings for urban planners, architects, and policymakers operating in comparable climates. Indeed, the research question that orients this paper is as follows: What is the potential impact of greening the systems of open small spaces and courtyards of buildings on improving the microclimate conditions of historical high-density, densely built-up districts in hot climates?

The work provides part of the results obtained in a wider research project PRIN-funded research project 'Definition of a handbook of guidelines for implementing climate neutrality by improving the effectiveness of ecosystem services in rural and urban areas' (GICNES), aimed at defining an energy-efficient decision support tool based on urban and open space characteristics.

2. The benefits of small open spaces for reducing UHI impacts: the role of courtyards

The transformation to green and permeable surfaces of small open spaces in cities characterised by high building density, is a key intervention for climate change adaptation and urban resilience. These spaces, which are often fragmented, are widespread in stratified cities, where the ratio of built-up areas to open spaces is strongly skewed in favour of the former type, and where the UHI phenomenon manifests itself with increasing intensity, making a spreading and widespread adaptation strategy essential.

Despite their key role from a micro-climatic point of view, these spaces are particularly challenging to transform because they require specific design solutions that respect the urban context, capable of combining conservation with the introduction of green and permeable elements. Moreover, these spaces are often used for urban functions that seem to conflict with the need for increased green surfaces, as they are mostly necessary to meet urban mobility and accessibility needs. This adds layer of difficulty because transformations must consider multiple and coexisting urban functions.

Beyond the contemporary emphasis on small open spaces, historical and regional evidence further illustrates how courtyards have long served as climate-responsive elements across regions, influencing thermal comfort and indoor conditions through architectural and vegetation strategies. Courtyards have historically featured building architecture in many parts of the world, like South America, Asia, and the Mediterranean area, as they are an effective way to cope with various climates, proving their widespread functionality and appeal (Pelorosso et al., 2017; Miśkowiec, 2023). These outdoor spaces have been used to improve thermal comfort in hot climatic territories by providing natural ventilation, daylight, and thermal mass through the strategic use of sunlight, wind, and shade to allow residents to engage in various outdoor activities (Almhafdy et al., 2013;

Azimi & Shafaat, 2024). Furthermore, the inner presence of vegetation is a simple yet effective way to control a building's indoor temperature and sunlight exposure (Gonzalez et al., 2025; Sadat et al., 2025).
In general, the inner courtyards of buildings, historically conceived as the lungs and articulations of urban life, housed citrus groves, vegetable gardens, and spaces of sociability that defined the environmental quality and the relationship between inside and outside. In these courtyards, a local micro-economy linked to subsistence agricultural activities was developed, providing, at the same time, an aesthetic and symbolic value that reflected the wealth and residential or mercantile function of the building. After World War II, the growing economic prosperity and the resulting urban expansion, at least in the European context, and the greater demand for private mobility, accelerated the conversion of many courtyards into parking lots, warehouses, or new buildings, resulting in a shift away from the agricultural and social function that courtyards had served for centuries (Gargiulo & Zucaro, 2023, Francini et al., 2021). This process has often resulted in the closure or transformation of frontages, the sealing of interior surfaces and the removal of tree rows, exacerbating the consequences of UHI, increasing surface runoff and worsening the quality of interior public space, which has progressively closed in on itself, hindering pedestrian access, natural light and the perception of safety.
In all these cases, the climatic functionality of the courtyard is consequently reduced, and it would be beneficial to restore these spaces, reconnecting them with their historical purpose, while also satisfying current requirements.
The need to reduce UHI impacts has prompted numerous studies investigating how microclimate changes within a courtyard by determining lower air temperature, resulting in energy consumption reduction due to lower energy loss through surfaces that are in contact with the courtyard itself, by reducing the usage of conditioning systems (Tabesh & Sertyesilisik, 2016; Azimi, 2024). For instance, Ghaffarianhoseini et al. (2015) and Zhu et al. (2023) demonstrate the influence of orientation, height, wall albedo, and vegetation in optimising courtyard performance in hot-humid climates. Bulus et al. (2017) and Natanian et al. (2019) found that in dry and hot climates like Kuwait, Iran, Tunisia, the Middle East, and Nigeria, the microclimate created by courtyards significantly improved indoor comfort: it decreased by over 88% the time with severe indoor discomfort and proved to be superior in terms of energy balance in free-running conditions.
Generally, most of the existing literature focuses the attention on geometry and design (e.g. orientation, surface materials, aspect ratio) of these urban places with the main aim to assess the potential improvements in boosting natural cooling, minimising energy demand for cooling and heat loss and reducing heating requirements by working at the building scale (Dody et al., 2025; Zheng et al., 2023; Zhu et al., 2023). Interactions between courtyard properties and the surrounding urban contexts where they are distributed are less frequently analysed, even if the weight and the extent of these links can be useful to cool the built environments. To contribute to filling this gap, the present work proposes climate-response greening reconversion of San Lorenzo district in Naples, characterised by the presence of numerous sealed courtyards nestled within this dense built-up fabric.

3. Method

To measure and interpret the numerous interactions among micro-climate (thermal comfort, air temperature, etc.), physical (geometry, surface materials, etc.) and geomorphological (slope, surface typology, etc.) characteristics of the system of open small spaces and courtyards and their urban context, the software ENVI-met is used. Compared to the other modelling tools like CitySim Pro, RayMan, and Grasshopper plug-ins Ladybug, ENVI-met results are one of the most effective for simulating the spatial distribution of thermal parameters in different climatic settings and urban assets, plus variations in building configurations and vegetation types (Zhnag et al., 2022; Kotharkar & Dongarsane, 2024; Ye et al., 2025).
This tool, developed by Bruse’s team in 1998, simulates vegetation-atmosphere-soil-building feedback through the laws of fluids and thermodynamics in 3D grid-based models that are now integrated in GIS environment.

Urban Data		
Physical characteristics	Building height, surface, Road width, length Outdoor surface materials	0000B1- Brick wall (aerated) 0200C3 - Concrete wall (hollow block) 0200PP-Pavement (Concrete), used dirty, Albedo:0.25 – Microscale roughness length 0.1 m
Geomorphological characteristics	Slope Vegetation	Land surface coverage within Copernicus DEM – GLO-30 (C.D.S.E., 2025) 0100XX-Grass 25 cm average dense 0100XY – Grass 50 cm average dense 01SLSM- Spherical, large trunk, sparse, medium (15m)
Climatic data		
Simulated day	July 31, 2024	
Simulated hours	14:00 - 15:00	
Time of Max Air Temperature	14:00	
Time of Min Air Temperature	05:00	
Time of Min Relative Humidity	16:00	
Time of Max Relative Humidity	25°C	
Min Air temperature	25°C	
Max Air temperature	34°C	
Min humidity	20%	
Max humidity	74%	
Wind speed at 10 m height	2 m/s	
Simulation Settings		
Grid size	x =3 m; y=3 m; z=3 m	
Model size	1000 m x 1000 m	
Simulated time	1 h	
Human Parameters (Biomet)		
Age	35	
Height	1.75 m (ISO 7730)	
Weight	75 kg	
BMI	18.5 - 24.9 kg/m2 (healthy weight)	
Clothes	0.90 clo in summer (pants or skirt and shirt made of thin fabric)	
Metabolic rate	164.49 (W)	

Tab.1 ENVI-met model settings and inputs

Existing studies demonstrate that material composition, vegetation, and shading affect microclimate conditions, supporting the use of ENVI-met to evaluate and optimise courtyard thermal performance (Soflaei et al., 2020; Diz-Mellado et al., 2021; Unal, 2025).

The ENVI-met Science version 5.7, released at the beginning of 2025, is used in this work, and the data required to run the simulations are summarised in Tab.1: urban and climatic data, simulation settings and personal characteristics for thermal comfort indexes calculation. The urban data refer to the characteristics of the urban system that are useful for the aims of this study: physical features of buildings, road network and open spaces and geomorphological ones related to the permeable soil, its slope and the existing vegetation. Raster images and vector data collected from available open databases are used to measure these characteristics and, consequently, to develop the 3D model of the study area in current and future greener scenarios, thanks to the interoperability between GIS and ENVI-met environments.

From Tab.1, it is also possible to read the materials in the ENVI-met Library, selected according to relevant physical properties (albedo, water absorption capacity, roughness, shading). If matching the 3D model elements is not possible, materials can be customised through the physical properties editor, allowing for realistic simulation (Darbani et al., 2023). This process allows a local library of interventions to be built, which is useful for comparisons between scenarios.

In parallel, the GIS layers needed to spatially represent the interventions are created, using software such as QGIS. Polygons and points describing surfaces to be modified, such as grassy soils, forested areas, and point trees, are digitized. Each geometry is coded through an identifying attribute, ensuring a consistent and georeferenced representation of the transformations envisioned in the project (Muniz-Gäal et al., 2019).

The climatic data are required to launch the simulations, and they refer to the hottest day of the year for the city of Naples on the basis of the historical meteorological archive provided by ilMeteo.it. The selected date is representative of a dry and clear summer day with peak summer conditions in a typical Mediterranean city, with high solar radiation and extreme air temperature.

The simulations were conducted in ENVI-met v5.7.1 on a domain of 1,000 × 1,000 m with a vertical and horizontal step of 3 m (grid size x=3 m; y=3 m; z=3 m), for a simulated duration of 1 hour (14:00–15:00), corresponding to the hottest time of day on 31 July 2024. The boundary conditions were taken from the historical archive for 31/07/2024 and were entered as: Tmin 25 °C (05:00), Tmax 34 °C (14:00), UR min 20% (20:00), UR max 74% (05:00), wind 2 m/s at 10 m. Given the district scale of our study and the need for multiple simulations, the chosen grid size ensures reliable results while maintaining practical processing times. The simulation date is July 31, 2024, a dry and clear summer day representing peak summer conditions in Naples with high solar radiation and extreme air temperature. The simulations covered a time interval from 2:00 to 3:00 pm, in order to focus on the most critical time in terms of microclimatic impact.

All the data in Tab.1 are used to compare the current scenario (sailed courtyards) and the greening one, simulated by planting trees and grass within the system of courtyards and open spaces localised in the selected district. The project greening scenario involves the creation of new green areas totalling approximately 0.1 km², distributed within the sample area subject to simulation, through the planting of 200 new trees and the permeabilisation of some currently impermeable surfaces. The selected area falls within a high-priority neighbourhood for intervention, according to the guidelines of the PAESC (Sustainable Energy and Climate Action Plan) of the City of Naples, which highlights the presence of high energy consumption, high thermal vulnerability of the population, risk of flooding and health costs associated with heat waves. For these reasons, it represents an emblematic urban context for assessing the effectiveness of adaptation strategies. The definition of the project scenario was supported by an analysis that considered the availability of open spaces, as well as compatibility with existing infrastructure and urban and cultural constraints. In fact, part of the area falls within the UNESCO Zone and areas subject to cultural heritage protection, conditions that limit the possibility of structural or invasive interventions. For this reason, the simulated scenario includes low-impact and temporary categories of intervention. Although no formal participatory process was conducted, the choice of intervention types is based on evidence from previous studies and municipal guidelines. These strategies are also consistent with the mitigation and adaptation objectives set out in the PAESC and municipal urban plans, presenting realistic scenarios that are potentially feasible in the medium term. The quantity and distribution of trees in the intervention scenario were defined based on the actual availability of open spaces suitable for planting, excluding areas that would interfere with traffic or that are not large enough to accommodate a canopy with an average radius of 5 m. As for green areas, "grass" was applied to all selected open spaces, not as a literal representation of a uniform lawn, but as a proxy for permeable surface material. In the ENVI-met library, the "Grass 25 cm" or "Grass 50 cm" category is the closest to the thermal and

hydrological characteristics of draining paving or urban flower beds and is therefore suitable for simulating the effects of widespread permeability in the consolidated urban fabric. This pervasive greening transformation allows for maximizing the thermal benefits induced by the presence of trees in all open spaces (public and private), representing a theoretical and ideal benchmark useful for assessing the maximum potential for microclimate improvement achievable in densely built urban fabrics, where single and isolated greening interventions may have smaller positive effects (both in terms of temperature reduction and the parts of the built environment that benefit) because of the intrinsic characteristics of the built environment itself.
On the other side, the simulation of the real scenario represents a fundamental step to understand the current climatic conditions of the urban area analysed and to define a useful baseline for comparison with the proposed intervention solutions. The use of ENVI-met makes it possible to assess the behaviour of the urban fabric under current conditions, highlighting the most critical areas and the main sources of thermal stress (Muniz-Gäal et al., 2019).
The objective of this phase is twofold: to provide a detailed determination of the current state; to further validate the model, verifying the consistency of the simulated results with the collected data. The simulation of the real scenario also allows the model parameters to be refined, improving its calibration according to the specific characteristics of the urban context. This phase thus constitutes an indispensable reference for assessing the effectiveness of the interventions simulated subsequently and for building a solid methodological basis to support urban planning and climate adaptation decisions.
This comparison between current urban assets and the potential whole green one allows us to assess the impact of heat-adaptation interventions on urban thermal comfort, including changes to surface materials (e.g., grass, water, concrete) and the introduction of 3D vegetation. The thermal comfort is evaluated using specific indices like the Physiological Equivalent Temperature (PET) and Mean Radiant Temperature (MRT). Selecting thermal indicators is a crucial step in microclimate research (Azimi & Shafaat, 2024; Liu et al., 2020). This study prioritises PET, UTCI and MRT over alternative indices due to their appropriateness for microclimate analysis and their pronounced sensitivity to radiative heat exchange, a factor of particular relevance in courtyard environments. MRT plays a key role in elucidating the effect of radiation on thermal perception, given that courtyards are strongly shaped by both direct and reflected solar radiation. Meanwhile, PET measures the actual sensation of heat perceived by people. PET, which uses MRT as input, provides a human-centric evaluation of thermal comfort by combining meteorological conditions with individual metabolic responses, thereby explaining its widespread application in urban heat mitigation research. Finally, It is important to measure UTCI because it provides a comprehensive assessment of heat stress for humans, taking into account temperature, humidity, wind, and solar radiation, to improve well-being and protect people's health.

Indicator	**Root Mean Square Error (RMSE)**	**Source**
PET	±2.0 – 2.5 °C	Koletsis, 2023; Zhao et al., 2021
T Aria	±0.44 – 3.05 °C	Tsoka et al., 2018; Liu et al., 2023
UTCI	±1.5 °C	Koletsis, 2023; Silva et al., 2025
RH	±3.88 – 8.70 %	Ouyang, 2021
SET	±1.8 – 2.4°C	Yuan et al., 2024
MRT	±6.08-13.32 W/m^2	Aleksandrowicz et al., 2023
Wind Speed	±1.63 m/s	Aleksandrowicz et al., 2023
LST	±2.0 – 4.0°C	Huang et al., 2015

Tab.1 RMSE of ENVI-met Microclimatic Indicators from Literature

As with any other simulation tool, the reliability of ENVI-met results should be carefully examined, also based on the simplification of input parameters and the size of the study area of the simulations to be performed. Therefore, in this study, the results have been validated by using the ranges reported in the literature relating to the Root Mean Square Error (Tab.2).

4. Study area

The study area is the San Lorenzo neighbourhood located in the historic part of the coastal city of Naples in southern Italy. The district is included within the fourth Municipality, with the neighbouring ones of Vicaria, Poggioreale and Zona Industriale, and together with that of San Giuseppe constitutes almost the entirety of the ancient centre of Naples, which immediately denotes its strongly compact and stratified layout (Fig.ss 1 and 2).

The lack of permeable spaces both in the study area and in surrounding areas reflects the significant influence that urban development and morphology have on the distribution and location of open and green spaces within the city. The density of buildings, the road network, and the type and distribution of buildings are among the main drivers determining the availability of open spaces, which vary considerably depending on the type of urban fabric.

In the historic area, characterised by high density and often by an organic or pre-planned urban structure with irregular layouts (e.g. medieval centres), the availability of permeable or unbuilt land is more than limited. This leads to a scarcity of large open and green spaces, which mainly take the form of small, fragmented areas such as squares, internal courtyards or historic gardens. Their potential effectiveness in terms of improving thermal comfort may be limited at the level of individual spaces, but their widespread integration can greatly contribute to enhancing the cooling effect, determined by the new presence of vegetation, as well as enhancing their value and cultural identity.

On the contrary, in more recently developed (post-war) areas, such as the peripheral areas, characterised by lower building density and, above all, greater availability of permeable areas, it is possible to integrate existing and newly created continuous open space systems. The urban layout in these contexts tends to be more regular, often based on road grids that can facilitate the creation of green corridors connecting open spaces. The latter are sometimes the result of a process of transformation that is not continuous over time, which can lead to the presence of isolated green spaces that require better connectivity between themselves and with the rest of the fabric in which they are located.

An analysis of the distribution of open spaces in the city of Naples, covering a total area of approximately 118,469 km², reveals significant disparities in the provision of green areas, with a clear distinction between the historic city centre and the suburbs.

In particular, the neighbourhoods with the highest presence of trees and wooded areas are located in the suburbs like San Carlo all'Arena, with the Capodimonte Forest, and Pianura, Fuorigrotta, and Bagnoli close to the largest forest areas and the city's main green lungs. Ponticelli and Poggioreale, although characterised by a strong presence of brownfield areas, have areas of spontaneous vegetation which, despite having a lower ecological value, contribute to increasing the amount of urban greenery. However, the quality of this greenery is uneven and requires redevelopment. In contrast, the historic central areas (San Lorenzo, Pendino, Avvocata, Stella, San Giuseppe, Porto) have a high building density and a scarcity of permeable surfaces, with courtyards and squares often completely impermeable.

The census data confirm these trends, although they are not complete: Table 3 and Figure 1 show that forest areas (approximately 8 km²) cover the northern urban ring, without benefiting the historic part of the city in terms of thermal comfort, where only 332 of over 4,400 courtyards have vegetation and/or trees inside them. Of 318 squares, only 45 have a percentage of greene ry greater than 50% of the total surface area, and of

575 parking lots, only 17 have vegetation cover. To conclude, out of 5,679 open spaces, a total of 5,295 have no vegetation, which is a worrying number, especially for the established historic central areas.

	N°	m²	Km²	% of the city area
Impermeable Sqaures	273	62.358,134	0,062	0,053
Green Squares (>50% of green areas)	45	494.262,570	0,494	0,417
Total Squares	318	556.620,704	0,557	0,470
Impermeable Inner Courtyard	4.454	916.813,431	0,917	0,774
Green Inner Courtyard	332	430.729,997	0,431	0,364
Total Inner Courtyard	4.786	1.347.543,428	1,348	1,137
Impermeable Parking Area	558	1.074.069,392	1,074	0,907
Green Parking Area	17	66.667,072	0,067	0,056
Total Parking Area	575	1.140.736,464	1,141	0,963
TOTAL Impermeable Open Spaces	5.295	2.053.240,957	2,053	0,000002
TOTAL Green Open Spaces	384	991.659,639	0,992	0,000001
TOTAL Open Spaces	5.679	3.044.900,596	3,045	0,000003

Tab.3 Average surface and amount of the different kinds of open spaces located in San Lorenzo district, compared to the whole city of Naples

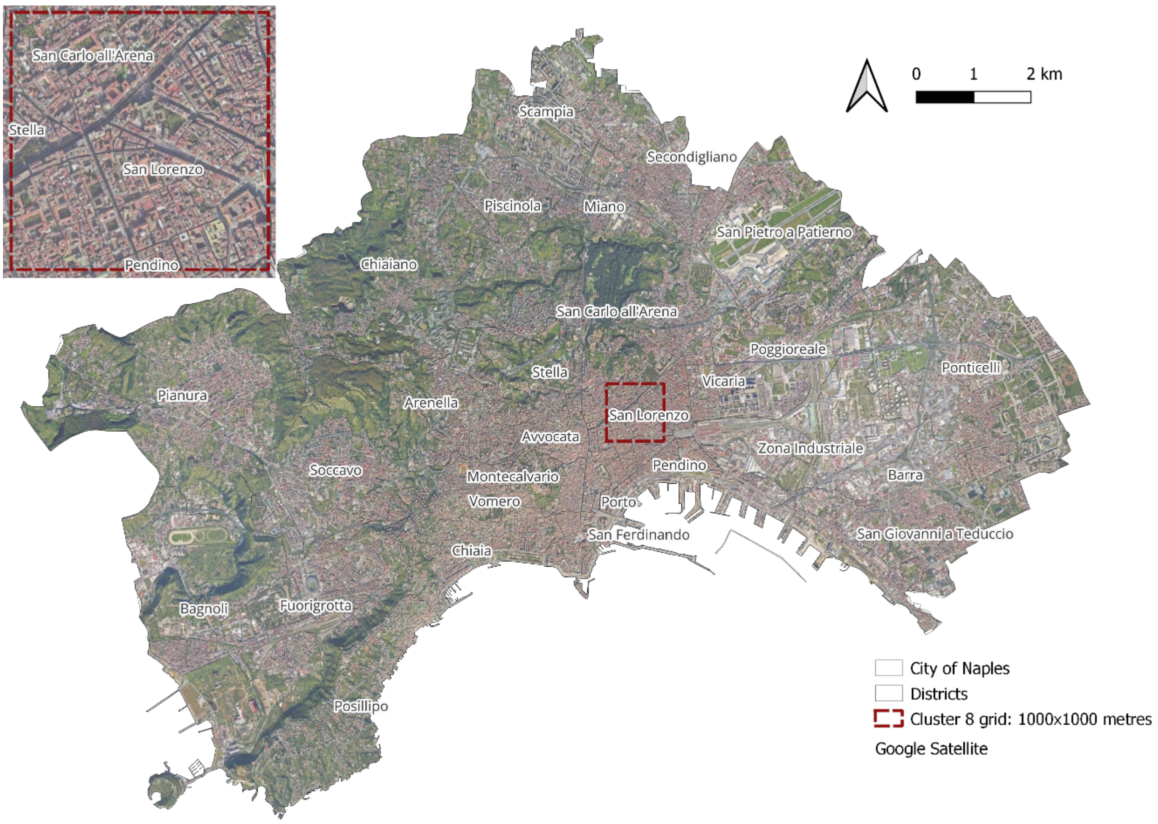

Fig.2 Study Area allocated in San Lorenzo District

Moving the attention to the district under study, San Lorenzo has been affected by the Naples Redevelopment Project promoted in 1885 and aimed at redefining the urban layout of the central-eastern part of the city through the construction of new residential buildings and road axes, to reorganise the urban layout of this part of the city, improving its usability and liveability for residents.

The settlement fabric of this district is characterised by the widespread presence of stately mansions, which, inside, contain square courtyards hosting, at one time, also gardens, citrus groves, vegetable gardens and social spaces that defined the environmental quality and the relationship between inside and outside (Fratini, 2023).

In fact, the layout and building pattern that strongly characterises San Lorenzo is representative of the typical "insule" (islands) of the city of Naples, i.e. building blocks consisting of single, large historic buildings where the open spaces inside, the cohorts, were used for agricultural, recreational and social purposes until, after the war, continuous sealing interventions converted them into areas for parking vehicles and/or for building (Fig.3). This progressive and inexorable transformation has led to the loss of their original functions, preventing greater and better use of them, even by those who live in the buildings to which these cohorts belong, and reducing their architectural and naturalistic value. Reclaiming this type of space, enhancing their original ecosystemic and recreational functions through their conversion to green areas, means improving the urban quality of large parts of cities where these spaces are pervasive and, above all, implementing targeted and effective adaptation measures in view of the dense urban context in which they are located (Lai & Zoppi, 2023). Therefore, San Lorenzo represents an interesting case study in applying greening interventions in densely built cities, due to its compact fabric, the high presence of open small spaces and courtyards, such as the lack of permeable surfaces. Furthermore, according to the first results of the research project, including this paper, San Lorenzo is among the districts that require prior climate adaptation interventions and solutions to reduce UHI effects and related energy consumption levels (Carpentieri et al., 2026).

Fig.3 Built-up areas, green areas and impermeable open spaces in the study area

5. Results and discussion

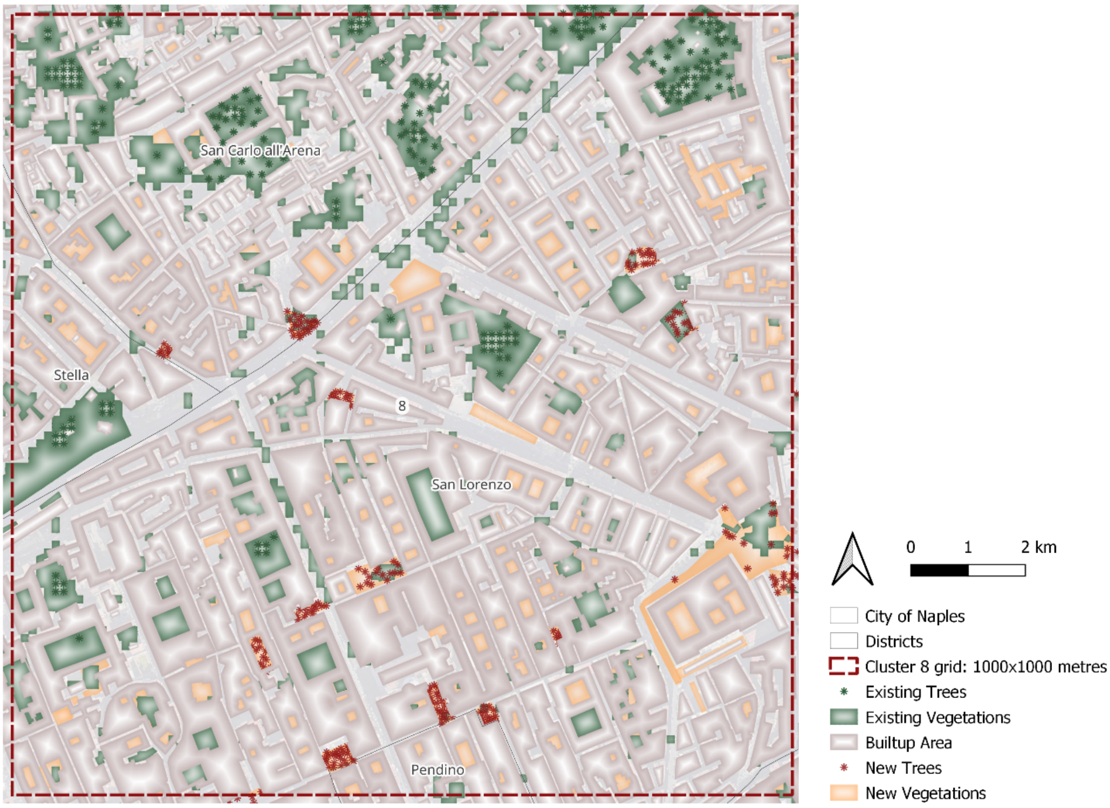

Fig.4 Real and interventions scenario layers of the selected study area

The results obtained for each of the three thermal comfort indicators considered are described below, reporting both the absolute values calculated in the simulations and the variations (Δ) obtained following the simulated greening interventions located in open spaces, courtyards and road axes in the San Lorenzo district.

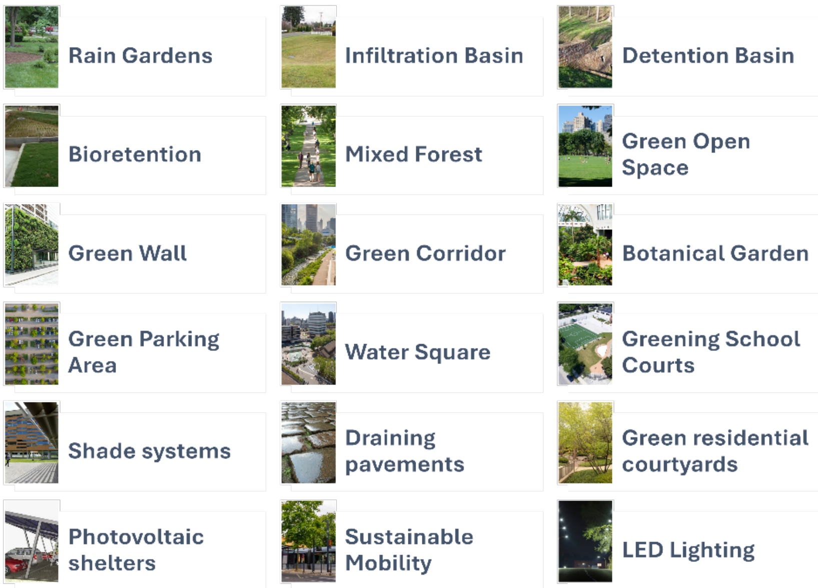

Fig.5 Climate change adaptation and energy saving interventions category

Although it is not possible to simulate specific interventions using ENVI-met software, it was decided to add vegetation layers of 25 and 50 cm, but these are translated into the list in Fig.5. Moreover, to reduce errors from ENVI-met outputs, an RMSE interval consistent with recent literature for each indicator was subtracted from the Real – Green Interventions difference (Tab.2).

5.1 ΔMRT (Mean Radiant Temperature)

Fig.ss 6 and 7 show that the ΔMRT variation (current scenario vs. simulated greening scenario), reduced by the RMSE error rate obtained from the scientific literature, shows significant reductions (>15 °C) localised around the new trees and "green islands" restored in the courtyards and squares, due to direct shading and the effect of screening the sky from solar radiation (reduction in the Sky View Factor value).

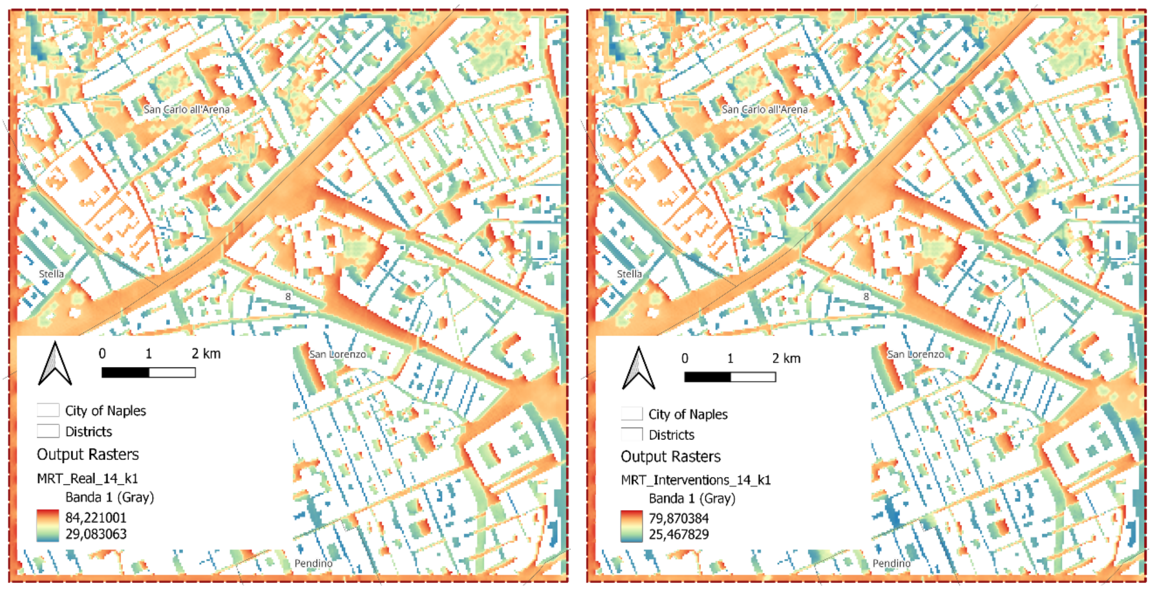

Fig.6 MRT absolute values distribution in the study area in the current scenario (left) and in the simulated one with greening interventions in open spaces and streets (right)

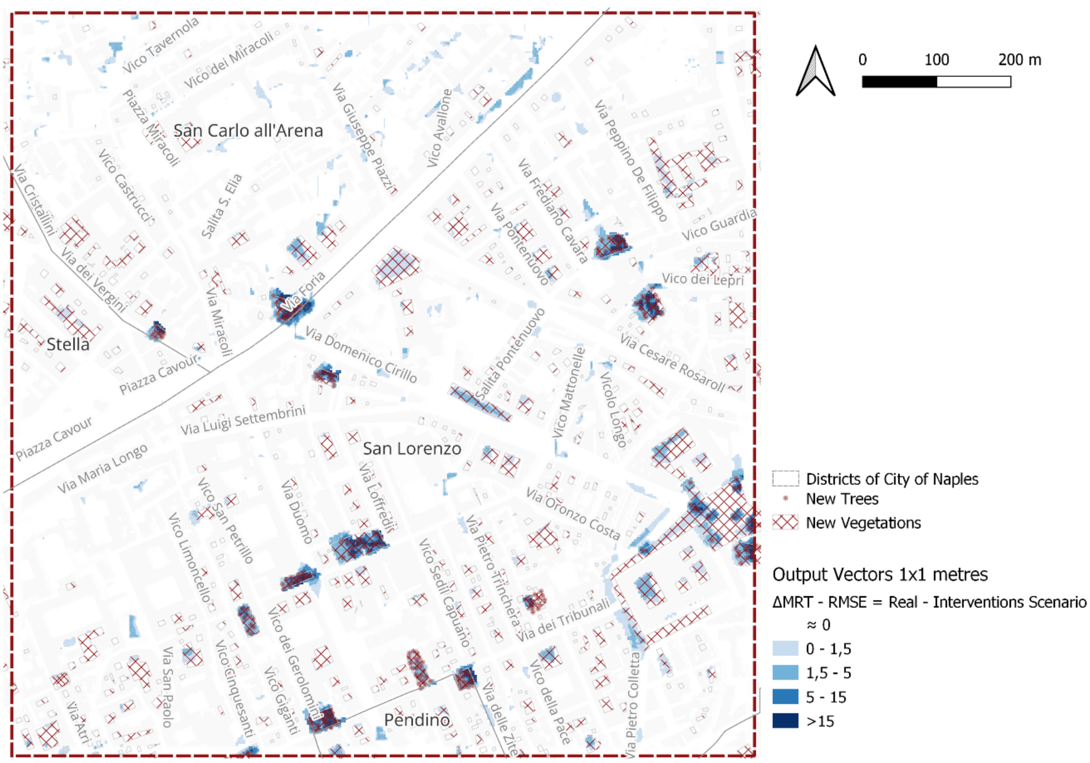

Fig.7 ΔMRT values distribution in the study area

The MRT value gradually decreases from open spaces to adjacent road axes, going from current values between 5–15 °C to 1.5–5 °C, which become almost irrelevant (≈0–1.5 °C) in small internal courtyards located near these spaces. These benefits are also attributable to the combined effect of the presence of (new) trees and the natural shade provided by the height and location of buildings along roads and in open spaces, which contributes to the reduction of incident and, in part, reflected radiation.

The validity of the MRT values obtained, as evidenced by the fact that no decreases are observable in open spaces where greening has not been proposed, even after subtracting the RMSE, indicates that the radiant effect of trees is immediate and limited, but more effective in terms of the surface area that can benefit from the presence of trees if extended over multiple road axes. In a fabric such as the stratified one of San Lorenzo, the precise but widespread choice of inserting green elements of this type can contribute to creating a diffuse network of cooling areas, which can affect the improvement of thermal comfort along the main and most frequented routes of the city district.

5.2 ΔPET (Physiological Equivalent Temperature)

Fig.9 shows that the reduction in PET (including the RMSE error rate) is distributed more uniformly and continuously within the study area than in the case of MRT: decreases in values between 3 and 6°C affect almost the entire San Lorenzo district, with "hot-spot areas" of 6–12°C (and locally >12°C) corresponding to the arboretums to be restored in the courtyard and also along some tree-lined axes connecting part of the open spaces.

This result is consistent with the very nature of PET, which integrates radiation, air temperature, wind speed and relative humidity: shading (MRT reduction) and evapotranspiration from the new vegetated surfaces contribute to this widespread benefit, thanks also to the increased ventilation along the roads.

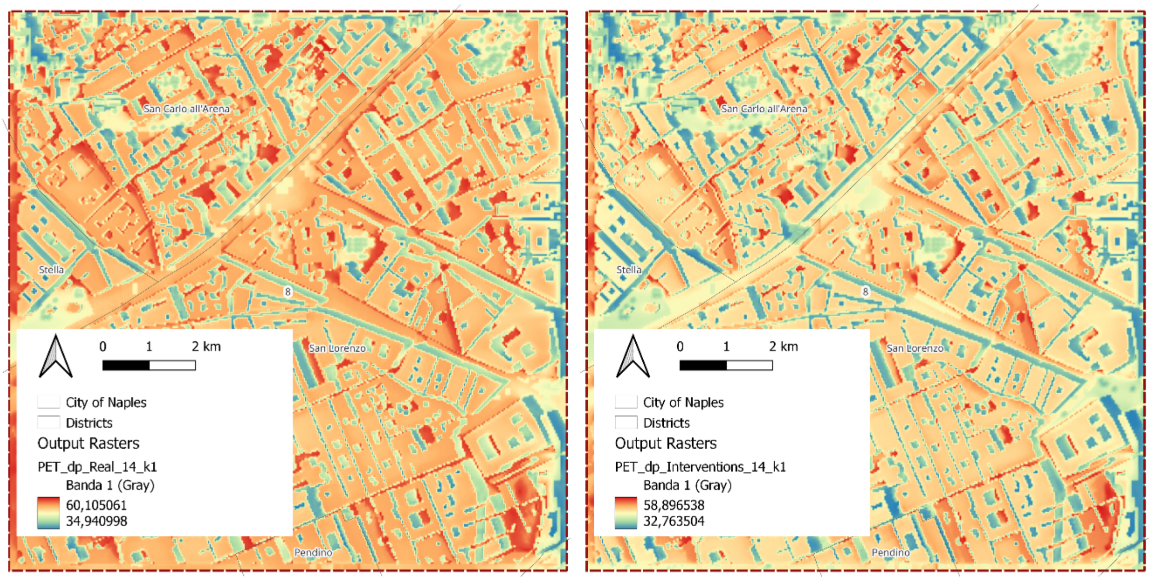

Fig.8 PET absolute values distribution in the study area in the current scenario (left) and in the simulated one with greening interventions in open spaces and streets (right)

This results in a reduction in the perceived heat stress not only in the proximity of linear greening interventions, but also in the surrounding areas (courtyard), with a plausible gradient along the canyon (Fig.8 and 9). Finally, it is worth noting that the widespread decrease in PET values between 0 and 3 °C mainly affects the main pedestrian paths, such as Via Foria and its cross streets, and the open spaces and courtyards that face them.

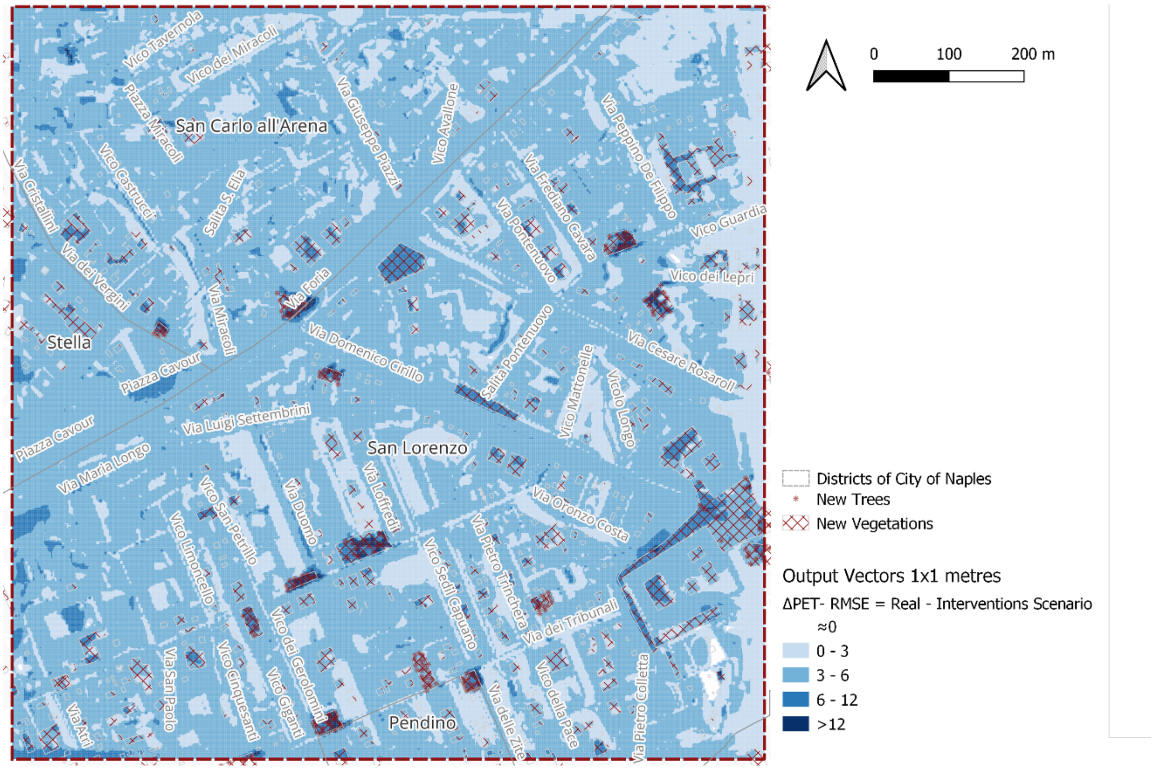

Fig.9 ΔPET values distribution in the study area

5.3 ΔUTCI (Universal Thermal Climate Index)

Fig.11 shows a more moderate variation in UTCI compared to the previous two indicators, PET and MRT. In fact, the classes with decreases in values between 0 and 1.5 °C and 1.5 and 3.5 °C prevail, with variations greater than 3.5 °C near the new trees and more extensive permeable surfaces.

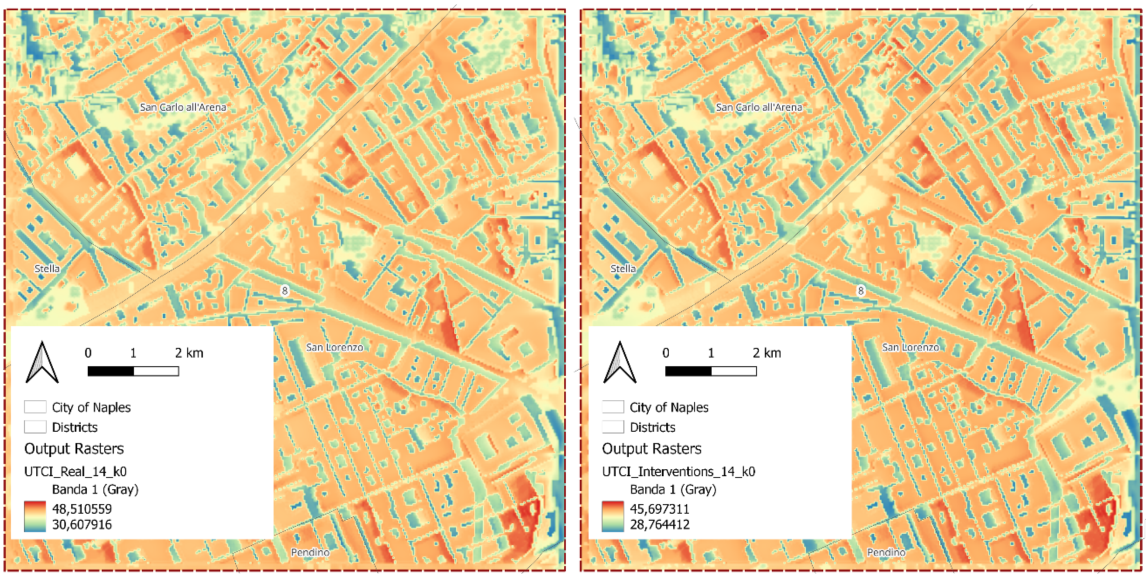

Fig.10 UTCI absolute values distribution in the study area in the current scenario (left) and in the simulated one with greening interventions in open spaces and streets (right)

The UTCI confirms a reduction in physical discomfort compatible with appreciable changes in comfort categories, for example, from "strong" to "moderate" (EEA, 2020), in the areas adjacent to the green axes connecting the restored gardens and citrus groves.

Fig.11 ΔUTCI values distribution in the study area

This improvement in thermal conditions for road users is reliable due to the RMSE rate subtracted and more than appreciable due to the fact that reductions of more than 1–1.5 °C are still found in the simulated peak hour (14:00) of the hottest day of the year (31/07).

6. Conclusions

This study aims to propose the restoration of the original functions of gardens and citrus groves in the inner courtyards of the San Lorenzo district (Fig.1), with a view to implementing distributed and interconnected greening interventions to increase the adaptive capacity of highly densified and stratified urban systems such as that of Naples.

Starting from the observation that the anthropogenic transformation of these spaces, from agricultural functions to car parks or warehouses, has generated degradation and climate vulnerability, the work has demonstrated how their conversion represents a strategic lever for the resilience of urban areas.

The simulations confirm that reforestation and permeability solutions can bring significant microclimatic benefits even in a dense and compact urban fabric such as that of San Lorenzo. The MRT, which measures the radiant energy perceived by the human body, shows the most marked reductions of over 15° in the areas immediately adjacent to the new trees, thanks to the shade and reduction in the Sky View Factor. The PET indicator, which integrates radiation, air temperature, humidity and wind to provide a direct measure of perceived thermal stress, shows a widespread improvement across the entire area, especially near internal courtyards and tree-lined avenues, where there are widespread reductions of between 3 and 6°. Finally, the UTCI, which translates microclimatic conditions into universal thermal comfort levels, confirms a more moderate but still significant reduction, with values generally between 1 and 3.5°, sufficient to shift the discomfort categories from "strong" to "moderate".

Overall, these results show that even targeted and widespread urban greening interventions can produce tangible and perceptible effects on microclimatic comfort, strengthening the resilience of historic districts to heat waves.

The conversion of open sealed spaces, even those of limited size, to green ones can produce measurable and significant benefits in terms of thermal comfort:

- capillary planting is the most effective solution for reducing the MRT, directly influencing comfort indices such as PET and UTCI in the canyons of the historic fabric. The contextual creation of lawns helps to increase the proportion of permeable surfaces capable of contributing to the cooling effect determined primarily by the presence of trees, favouring rainwater runoff;
- the integration of interventions in courtyards, streets and squares reinforces the cooling effect obtained from their greening and proximity, creating corridors and pedestrian areas of thermal comfort that make the urban environment more liveable, attractive and resilient. Courtyards, especially if made accessible or semi-public, act as "emitters" of radiant cooling towards adjacent streets, improving the local temperature gradient;
- in areas subject to protection restrictions, the adoption of soft, non-hard and reversible interventions (e.g. linear flower beds, compatible trees, draining paving, removable shading system) proves to be a particularly effective strategy for balancing heritage conservation with the need for climate adaptation.

Summarizing, this study demonstrates that widespread conversion to green and permeable surfaces, even on a micro scale, can significantly reduce the main summer comfort indices, stating that priority interventions have to take into consideration not only large parks, but also, and above all, courtyards and streets in historic centres.

The positive effects of increasing greenery on UHI reduction and runoff management improvement are clear to see in contexts such as the district under study, which has high energy consumption and a tendency to flood (Carpentieri et al., 2024 and 2026; Gargiulo & Zucaro, 2023). These results provide a solid basis for local administrators, technicians, designers, real estate companies and citizens called upon to define and implement targeted adaptation strategies. In this context, even small transformations (e.g., courtyards and parking areas made permeable or planted with trees) have a significant impact on microclimate quality, thanks to a widespread overlap effect. It is therefore necessary to enhance large forested and disused green areas and to take widespread action on smaller open spaces, which represent the real potential for climate adaptation in the historic centre.

7. Study limitations

While providing significant results, the present study can be deepened from a methodological point of view, offering opportunities for future research. The simulation was targeted at an extreme day and time, and the data on vegetation and buildings are not detailed by species, type or seasonality. This was a conscious methodological choice, aimed at clearly measuring the impact of the interventions, leaving ample room for improvement in this direction.

In the future, we intend to extend the simulation to a longer time frame and to integrate more precise botanical data (e.g. species, seasonal LAD - Leaf Area Density) in order to obtain even more accurate outputs. It would also be valuable to explore the social and economic impact of these interventions, assessing aspects such as increased biodiversity, improved air quality, perception of safety and strengthening of local identity. This more holistic approach would allow for a full quantification of the environmental, social and economic capital returned to the territory, providing a more comprehensive assessment of the sustainability of the proposed strategies.

Acknowledgments

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Fig.7: authors' elaboration;

Fig.8: authors' elaboration;

Fig.9: authors' elaboration;

Fig.10: authors' elaboration.

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