

Article

Counteracting Urban Thermal Hot Spots in Florence, Italy: The Combined Effects of Vegetation and High-Albedo Surfaces

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Abstract

As cities increasingly face extreme heat, urban planning plays a crucial role in mitigating the urban heat island effect through sustainable cooling strategies. This study investigates the combined potential of vegetation and high-albedo surfaces to reduce urban heat while providing additional ecological benefits in a public square in Florence (Italy). Currently dominated by asphalt, the square represents a summer thermal hot spot, with surface temperatures reaching 50 °C. Using QGIS, ENVI-met, and i-Tree Eco, existing conditions were compared with a redesign scenario including 87 new deciduous broadleaf trees (resulting in a total of 90 trees in the design scenario), 37% permeable green surfaces, 12% semi-permeable parking areas, and 51% high-albedo pavements. Simulations show summer average reductions of about 0.7 °C in air temperature and 6 °C in surface temperature, with maximum reductions of 1.3 °C and ~13 °C on average across the square (up to 20 °C locally under tree canopies and over high-albedo surfaces), reducing “strong” thermal stress areas by 50–60%. Additionally, the new trees provide ecological benefits, including pollutant removal, oxygen production, carbon sequestration, and stormwater interception. This study highlights the importance of predictive microclimatic assessment to optimize urban design and prevent unintended consequences.



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1. Introduction

Urban areas worldwide are increasingly experiencing the effects of the urban heat island (UHI) phenomenon, where urban temperatures exceed those of surrounding rural zones due to anthropogenic heat emissions, extensive impervious low-albedo materials, and limited vegetation [1,2]. Increasingly, thermal anomaly zones now extend beyond city centers, forming a complex “Intra-Urban Heat Archipelago” [3]. In Mediterranean cities, where climate change exacerbates thermal stress, counteracting the UHI is a key priority

for enhancing urban comfort and sustainability [4,5]. Internationally, urban planning plays a crucial role in addressing these challenges through integrated sustainable cooling strategies [6,7]. Among these, Green–Blue–Grey infrastructure (GBGI) solutions, combining vegetation, water elements, and reflective materials, offer synergistic benefits for thermal comfort and energy efficiency [8–11]. Vegetation cools the environment through shading and evapotranspiration, while high-albedo surfaces reduce solar heat absorption, jointly lowering ambient temperatures [10,12]. Empirical evidence confirms their effectiveness. In Sydney, high solar reflectance and green surfaces reduced peak ambient temperature by up to 3 °C [13], while in Riyadh (Saudi Arabia), combining cool materials with greenery, achieved reductions up to 4.5 °C and improved human thermal comfort indices by 20% [14].

Furthermore, over the past decade, advances in computational modeling, particularly using tools such as ENVI-met [15], enabled detailed simulations of microclimatic dynamics and the assessment of cooling strategies under varying urban configurations [11,12,16].

The present study applied this approach to Florence (Italy), a dense, historic city facing significant UHI challenges, to identify targeted strategies for urban thermal hot spots and develop a model that is transferable and replicable in other urban contexts. The research was conducted within the project “Monitoring and mitigation of climate change and promotion of biodiversity: the Florence model”, funded by the Capellino Foundation (<https://fondazionecapellino.org/it/fondazione-capellino>, accessed on 17 September 2026), which aims to develop an interdisciplinary framework for studying urban biodiversity and counteracting positive thermal anomalies in Florence. Based on previous research on green, reflective interventions and urban forms [17–19], this study employed a simulation-based approach to assess the combined effects of vegetation and high-albedo materials on urban microclimate. This predictive modeling framework supports a shift from reactive responses to proactive, evidence-based urban design, allowing site-specific strategies for climate-resilient development. The analysis focused on a public square in Florence, identified as the largest surface thermal hot spot in Florence [20], characterized by extensive asphalt coverage and commercial activities. Using ENVI-met simulations, daytime and nighttime thermal conditions were compared between the current state and the proposed design scenario, quantifying the cooling potential of combined greening and reflective interventions. By integrating simulation results with local environmental data, the study further evaluated multiple ecological and thermal benefits of urban trees. This provides actionable insights for sustainable urban planning and a methodology transferable to other cities facing similar UHI challenges.

2. Materials and Methods

2.1. Study Area

This study was conducted in the municipal area of Florence, located in the Tuscany region of Central Italy. According to the Köppen–Geiger climate classification [21], Florence exhibits a borderline Mediterranean (Csa) and Humid subtropical climate (Cfa) with a moderate influence from the sea and hot summers. July and August are the warmest months, and January is the coldest month of the year (source: <https://www.lamma.toscana.it/en/>, accessed on 17 September 2026). Based on the 1991–2020 climatological dataset, the summer months show average and maximum monthly temperatures of 22.6 °C and 29.1 °C in June, and approximately 25.0 °C and 32.0 °C in both July and August. Winter months are characterized by average and minimum monthly temperatures of 6.7 °C and 2.1 °C in January, 7.6 °C and 2.5 °C in February, and 7.1 °C and 2.8 °C in December. Specifically, the study focuses on a public open space (Artom Square) in a semi-central zone of District 5 of Florence, near one of the entrances to Tuscany’s largest multipurpose food center (Mercatir). The area is predominantly flat at an elevation of 44 m above sea level, and is classified as

Local Climate Zone 8, “large low-rise” [20]. Artom Square currently serves as a parking lot for vehicles accessing the “Mercafir” market.

2.1.1. Current Scenario

The area has an irregular, composite shape (spanning 7 sides) and covers approximately 5100 square meters. It is currently dominated by asphalt surfaces, with little vegetation, and surrounded by buildings mostly of 1–4 stories, ranging in height from 3 to 15 m. Satellite analyses of land cover and land consumption [20] confirmed the area’s high level of artificialization, with approximately 98% of the area covered by impervious surfaces (asphalt) and only 2.1% consisting of bush and grass cover. Strategically located within the urban fabric, the study area is near the University Hub, various commercial services, the Florence Airport, and the A1 motorway. Recent studies [3,20–22] identified climatic hazards linked to extreme temperatures in this study area. They revealed high-intensity surface urban heat islands and severe surface positive thermal anomalies (hot spots) that compromise its livability. Thermal hot-spot analyses applied to Landsat-8 thermal data revealed that Artom Square lies within Florence’s largest thermal hot spot, with pavement surface temperatures reaching approximately 50 °C in summer (average data around noon for the period 2013–2023). A three-dimensional view of the study area (Figure 1) highlights the extent of the positive thermal anomaly, with a color gradient from yellow to red representing hot spots based on specific confidence thresholds. Yellow, orange, and red colors correspond to confidence levels of 90%, 95%, and 99%, respectively.

Beyond climatic challenges, the area also faces urban issues related to its social and functional aspects. Surrounded by office buildings on 5 sides, the space lacks the typical features of public urban squares, such as shared spaces for citizens and workers, seating, or tree-shaded zones.

2.1.2. Design Scenario

The design of the square was developed following the general principles outlined in the regulations provided by the City of Florence. These regulations, to be formally adopted in 2025, define the required shaded areas in accordance with recommendations such as maintaining at least 30% tree cover [23] and selecting plant species from an approved list suited to the city’s climatic conditions and compatible with the existing urban vegetation.

The project procedure included a preliminary survey of existing functions and an assessment of the phytosanitary status of the plants. This process led to the development of a master plan for the area, aligned with a new vision jointly defined with the Department of Environmental Affairs of the City of Florence. The overall design approach required evaluating several strategies and selecting those best suited to the project’s main objectives: enhancing biodiversity and counteracting the local impacts of climate change. These goals were pursued primarily by reducing ambient temperature (through increasing shaded areas and improving pavement albedo) and by decreasing flood risk (through enhancing surface permeability and creating new rain gardens and bioswales). Where possible, plantings were arranged in multilayered structures comprising trees, shrubs, and grasses to increase the Leaf Area Index (LAI) of each individual space. Additionally, following the recommendations of the research group, plant species biodiversity was increased to support a wider range of pollinators. Structures such as pergolas and public building façades were also covered with climbing plants to further improve the microclimate and overall biodiversity of the area.

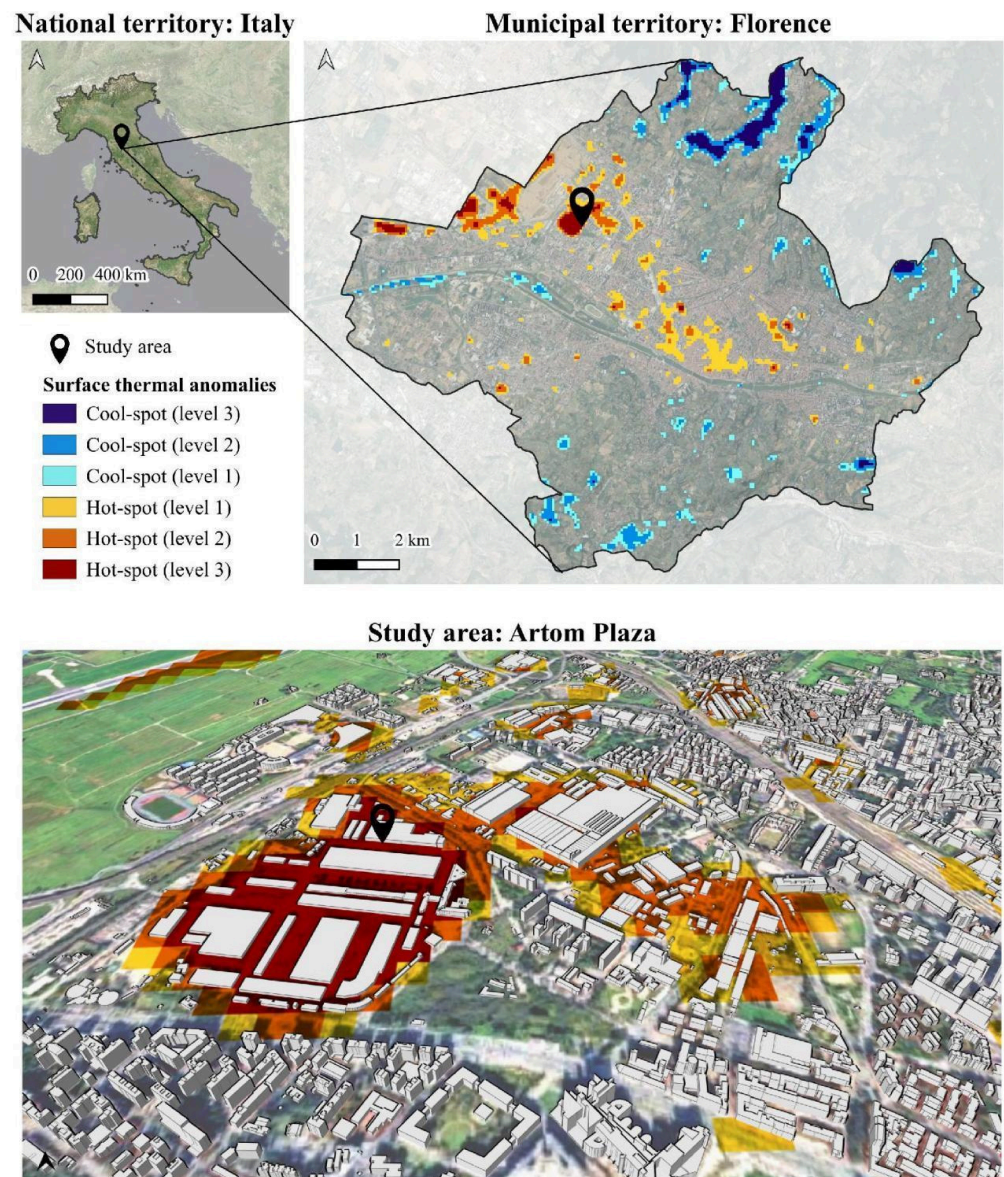


Figure 1. Study area.

2.2. Methodological Framework

This research involves diverse and structured activities aimed at generating data and indicators to assess thermal patterns, with a focus on comparing the current situation (ex-ante) and the proposed design scenario (ex-post). The analysis focuses on the summer and winter solstices (21 June and 22 December) of 2023, representing opposite thermal conditions within the year.

The research is structured into the following phases:

1. Analysis of urban morphology and shading potential in the current configuration of the study area. LiDAR surveys were used to develop 3D urban morphology models and shade indicators, identifying areas most exposed to solar radiation;
2. Surface measurements and characterization of urban and vegetative components in the current (ex-ante) scenario. Phase 1 digital model analysis and in-situ monitoring (including the use of an albedometer) were used to characterize the geometry, dimensions (x, y, z) of built volumes and green elements, materials and surface albedo;
3. Collection of meteorological parameters from ERA5 datasets. Localized meteorological parameters (including air temperature, wind direction and intensity, relative humidity,

- long-wave radiation, and short-wave direct and diffuse radiation) were collected to build up the meteorological datasets required for the summer and winter simulations;
4. Modeling of urban and climatic characteristics for current (ex-ante) and design (ex-post) scenarios. Spatial digitalization captured urban geometry, surface characteristics, and climatic conditions to develop realistic ex-ante and ex-post models;
 5. Urban microclimatic simulations for ex-ante and ex-post scenarios. Hourly summer and winter simulations produced 1 m resolution thermal and outdoor heat stress indicators;
 6. Tree-related simulations in the ex-post scenario. The effects of newly introduced trees were modeled for both the initial planting phase and after 10 years of growth, assessing gross carbon sequestration, pollutant removal, evapotranspiration, oxygen production, and avoided runoff.

Four tools were used in this study for their respective analyses: QGIS (version 3.34) [24] with the UMEP plugin (version 2.0.35) [25] for urban characterization and shadow analysis; ENVI-met (version 5.8) [15] and i-Tree Eco (version 6) [26] for climate and tree-based environmental simulations; and R software (version 4.3.2) [27] for geospatial and statistical analyses.

2.3. Urban Morphology and Shadow Analyses

This phase analyzed two key aspects of the study area's current conditions:

- Urban morphology, assessed through LiDAR data acquisition, and the development of digital models of terrain, buildings, shrubs, and tree canopies;
- Shading analysis and potential solar exposure of surfaces, derived from processing the aforementioned models.

The spatial data obtained in this phase were used to create a database characterizing the area's surfaces, essential for microclimatic modeling and simulations, and supporting the study's broader objectives. Average values of the previous spatial indicators were extracted in the study area by using the zonal statistic tool in QGIS [24] and R software [27].

Each analysis stage was conducted in the QGIS environment using FUSION (version 4.40) and UMEP plugins [25], with the resulting data available in GIS-compatible formats.

Urban morphology was analyzed using LiDAR data collected with the ZEB HORIZON device (GeoSLAM Ltd., Ruddington, Nottingham, UK), based on SLAM (Simultaneous Localization and Mapping) technology, providing precise spatial positioning (millimeter- to centimeter-level accuracy) and high-resolution point-based 3D data capturing morphological and elevation information for urban and vegetative features. The LiDAR point cloud was georeferenced using the HIPER HR Global Navigation Satellite System and integrated with 1 m resolution open-source digital models from the Municipality of Florence, ensuring seamless alignment for urban-scale analysis in QGIS. The following models were developed at a 1 m spatial resolution:

- Digital Terrain Model (DTM): represents terrain morphology, excluding built and vegetative elements;
- Digital Surface Model (DSM): captures the Earth's surface, including vegetation and built structures;
- Building Digital Surface Model (BDSM): represents the morphology and heights of buildings;
- Canopy Digital Surface Model (CDSM): reflects the morphology and heights of vegetative elements (shrubs and trees).

The shading analysis, based on the developed models, identified areas of potential solar exposure that require consideration in urban planning. Using elevation data for terrain, buildings, and vegetation, the following shading indicators were constructed:

- Daily Shadow Pattern (DSP): estimated based on the sun's position at specific times, with values ranging from 0 (shadow areas) to 1 (sunlight areas);
- Sky View Factor (SVF): a dimensionless parameter representing the proportion of visible sky from a given point at ground level, with values ranging from 0 (limited sky visibility) to 1 (high sky visibility). Higher values indicate greater exposure to solar radiation, while lower values correspond to more shaded surfaces [28].

These shading indicators were developed at a 1 m spatial resolution and analyzed for summer (21 June) and winter (22 December), incorporating seasonal vegetative parameters such as light transmissivity or shortwave radiation. These indicators are widely used in various scientific disciplines, including biometeorology, climatology, urban planning, and archaeology [29]. The SVF is a valuable indicator, complementing other parameters of the urban geometry such as the Urban Aspect Ratio (height-to-width ratio), along with further urban surface features (such as albedo, vegetation indices, etc.), for investigating thermal behavior in urban districts and assessing their climate vulnerability to specific risks, such as heat waves [30]. In particular, the SVF is influenced by urban fabric components, street furniture, and the presence of trees. Urban spaces can be classified based on SVF values as dense ($SVF < 0.25$), semi-dense ($0.25 < SVF < 0.50$), semi-open ($0.50 < SVF < 0.75$), and open ($SVF > 0.75$) [31].

2.4. Surface Measurements

The characterization of the area involves the identification and analysis of the main components of the study area in its current state (buildings, surfaces, and vegetation), based on geospatial data processed in previous phases, field surveys, and information retrieved from available regional and municipal databases. Specifically, the following elements were examined:

- Urban surfaces and building volumes: geometry, height, materials, and thermal properties (e.g., albedo);
- Vegetation: height, canopy dimensions, and tree species (if applicable).

Building and tree heights, as well as canopy dimensions, were obtained from the digital models developed in the preceding phase (Section 2.3). Tree species data were enhanced through field surveys and integration with the 2024 public tree dataset managed by Florence's Municipal Administration.

Ground cover and building material data were gathered through field surveys and analyzed from aerial imagery. Specifically, the albedo of paved surfaces was measured using an albedometer (LP PYRA 06, Delta OHM S.r.l., Caselle di Selvazzano, Padua, Italy). This instrument, leveraging a pair of thermopile sensors, measures surface brightness by calculating the difference between incident and reflected radiation. Albedo measurements were conducted on 10 May 2024, between 11:45 am and 12:45 pm, under clear skies with no cloud cover, at five representative paved sites. Simultaneously, surface temperature (ST) values were recorded at the same sites using a FLIR E8XT thermal imaging camera (FLIR Systems, Inc., Wilsonville, OR, USA), allowing direct comparison between surface temperature and corresponding albedo measurements. These surveys required clear, cloudless skies and no recent rainfall, ensuring accurate assessment of the surfaces' optical and thermal properties. The five survey points were selected to represent the limited range of paved surface types physically present within the study area (Artom Square), which is characterized by highly homogeneous land cover ($\approx 98\%$ low-albedo asphalt). Accordingly, the survey points were intended to characterize the on-site surface materials relevant to the

ex-ante model, rather than to capture the broader diversity of pavement types across the municipality of Florence.

2.5. Meteorological Data Collection

Collecting meteorological data for the intervention area is a crucial step in building the datasets required for climate simulations. ERA5 data for the summer and winter solstices of 2023 were collected from 20–21 June and 21–22 December. This approach provides a minimum 48 h period to simulate the typical climatic conditions of the Summer and Winter Solstices, as detailed in the next chapter.

ERA5 is the fifth-generation ECMWF reanalysis dataset, providing hourly estimates of a wide range of atmospheric, oceanic, and land-surface variables from 1940 to the present, at a spatial resolution of approximately 27 km (source: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>, accessed on 17 September 2026). A key advantage of using globally gridded reanalysis data is their high transferability and replicability, allowing the proposed microclimatic modeling workflow to be readily applied to other urban areas worldwide, particularly where localized meteorological observations are unavailable. Within this workflow, ERA5 is used primarily to provide the meteorological boundary forcing for the simulations and, secondarily, as a consistency reference for assessing whether the simulated near-surface air-temperature fields remain consistent with the prescribed large-scale atmospheric conditions. Importantly, ERA5 is not used as an independent validation dataset, since the reanalysis data are part of the model forcing. Independent validation is instead based on the in-situ observations collected by the nearby AirQino microclimate sensors. This strategy of driving ENVI-met with ERA5-derived boundary conditions has recently been applied in an Italian context by Cherchi et al. [32], who extracted ERA5 hourly data (1940–present) to identify a representative “typical critical day” subsequently used as input for ENVI-met simulations of a historic village in Sardinia. Consistent with this approach, and reflecting its growing standardization, ENVI-met version 5.8. within its ENVI-Guide interface, includes a dedicated function for the automatic retrieval of ERA5 meteorological data and the identification of typical days. Extracted parameters included air temperature at 2 m above ground (°C), relative humidity (%), wind direction (°) and wind speed at 10 m above ground (m/s), precipitation (mm), both direct and diffuse shortwave radiation (W/m^2), and longwave radiation (W/m^2). These parameters form the basis for climate simulations and are essential for accurately representing the study area’s environmental conditions during the solstice periods. In addition, model validation was performed using local meteorological data recorded at a nearby monitoring station (from the AirQino platform, source: <https://www.airqino.it/en/>, accessed on 17 September 2026), focusing on winter and summer months (December and June) and solstices, and verifying R2 and the Pearson Correlation Coefficient (PCC).

2.6. Urban Climate Modeling

The modeling phase, preceding the microclimatic simulations, involved digitizing climatic characteristics, urban components (buildings and pavements), and vegetation (permeable green surfaces, shrubs, and trees), and their volumetric and material properties (e.g., albedo). Both ex-ante and ex-post design solutions were converted into GIS spatial elements through georeferencing and the digitalization of pavements, vegetation, and pergolas.

The urban climatic modeling process was conducted in two phases:

- Development of a GIS database to capture surface, volumetric, and material characteristics of the area for both the ex-ante and ex-post scenarios;

- Transformation of the GIS database into a 3D ENVI-met model using QGIS and the “Geodata to ENVI-met” plugin (source: <https://github.com/One-Click-LCA/geodata2ENVI-met>, accessed on 17 September 2026).

In this work, the modeled area, covering an extent of 180 m × 180 m with a 1 m resolution, focuses on the study site and is appropriate for assessing urban-scale thermal patterns.

Data from urban, vegetative, and meteorological analyses were organized in GIS format (shapefile) with attributes like height and material type, then imported into ENVI-met to create 3D environmental climatic models, integrating both urban geometries and the local microclimatic characteristics of the study area. Four 3D spatial models—ex-ante and ex-post for the summer and winter scenarios—were used in ENVI-met to simulate seasonal thermal patterns.

In this study, average default values were used to model physical tree properties: an average foliage shortwave albedo of 0.18; emissivity of leaves of 0.96; and average Leaf Area Density (LAD) values of 1.0 and 0.3 were defined in summer (June) and winter (December), respectively. Since site-specific vertical LAD profiles for young/developing urban trees in Florence are currently unavailable in the literature, the use of these default ENVI-met values represents a widely accepted and standardized approach in microscale modeling.

Tree settings included leaf type (deciduous/conifer leaves), height and canopy width data, defined by ex-ante measurements and design selection. Green surfaces (grass, flowery meadow, bush, and green facades) were modeled by setting vegetation height and LAD. Although localized, custom soil and root parameters (such as dynamic in-situ soil humidity and initial temperature) were not customized due to the lack of specific field-measured soil data, the cooling and thermodynamic effects of bioswales, rain gardens, and grass were represented by selecting ENVI-met’s standardized database templates (such as humid grass and bush profiles). These templates are pre-calibrated with high default moisture availability, allowing the model to realistically simulate well-watered conditions and their associated transpirational cooling benefits.

The main ENVI-met settings modeled in the ex-ante and ex-post scenarios, including surface characteristics and albedo values, are provided in Table S1 of the Supplementary Materials.

2.7. Climate Simulations

The simulation settings were characterized by the following parameters:

- Spatial resolution: 1 m, the highest achievable resolution for urban-scale simulations in ENVI-met, enabling detailed assessment of local climatic conditions;
- Temporal resolution: hourly data modeled for two seasonal reference days, corresponding to the Winter (22 December) and Summer (21 June) solstices of 2023. These dates were selected to examine the simulated microclimatic response under summer and winter radiative conditions and were not intended to represent the full meteorological variability of the respective seasons.

Simulations for the ex-ante and ex-post scenarios were run in ENVI-met over 48 h in each season, based on meteorological conditions from the Summer (20–21 June 2023) and Winter (21–22 December 2023) solstices. The Indexed View Sphere (IVS) module was enabled to improve the accuracy of radiative heat transfer calculations, accounting for multiple interactions among surfaces, buildings, and vegetation. For the ex-post scenarios, deciduous broadleaf trees were modeled at 10-years post-planting, considering the corresponding morphological characteristics (height, crown diameter and leaf area density).

Simulations were performed with ENVI-met v 5.8 using the full forcing mode, with a spin-up of 24 h preceding the selected summer and winter days. The vertical grid comprised 40 cells, and 20 nesting grids were added at the domain boundary. UTCI was

computed with the BIO-met post-processing module, with the mean radiant temperature evaluated at 1.5 m above ground.

A series of comparisons was performed for two reference days (21 June 2023 and 22 December 2023), using three complementary sources of information:

- Simulated ex-ante air temperature from ENVI-met versus ERA5 reanalysis data, which were used to provide the meteorological boundary forcing. This comparison was performed as an internal consistency check, rather than as an independent validation, because ERA5 is part of the model forcing;
- ERA5 ex-ante air temperature versus independent in-situ observations from the nearby AirQino station, providing a quality assessment of the boundary forcing and its representativeness for the study area;
- Simulated ex-ante surface temperature from ENVI-met versus FLIR thermographic measurements, providing an independent assessment of the simulated surface temperatures; these measurements were available for the summer reference day only.

For the ENVI-met comparisons, the simulated output was spatially averaged over the domain to match the spatial and temporal resolution of the reference data. For each comparison, standard error metrics—coefficient of determination (R^2), Pearson correlation coefficient (PCC), mean bias, mean absolute error (MAE) and root-mean-square error (RMSE)—were derived.

Three indicators (in $^{\circ}\text{C}$) were selected to characterize the outdoor thermal patterns at 1 m resolution, both day and night: air temperature (T) at 1.5 m above ground, surface temperature (ST), and the Universal Thermal Climate Index (UTCI). UTCI, expressed as equivalent temperature ($^{\circ}\text{C}$), was used to quantify and spatially evaluate outdoor thermal stress levels in each scenario. As the state-of-the-art rational biometeorological index for outdoor environments [33], UTCI has been internationally applied across various sectors, including occupational thermal stress [34]. It integrated advanced clothing models for human thermoregulation and air temperature to predict the impact of outdoor climate on a reference individual: a 35-year-old person, approximately 1.70 m tall and weighing 73 kg, walking at a speed of 4 km/h and generating a total metabolic rate of $\sim 135 \text{ W/m}^2$, classified as moderate activity under international standards (UNI EN ISO 8996:2004 [35]).

UTCI categorized thermal stress into ten classes based on equivalent temperature [33]:

- Extreme heat stress: $\text{UTCI} > 46^{\circ}\text{C}$;
- Very strong heat stress: $38^{\circ}\text{C} < \text{UTCI} \leq 46^{\circ}\text{C}$;
- Strong heat stress: $32^{\circ}\text{C} < \text{UTCI} \leq 38^{\circ}\text{C}$;
- Moderate heat stress: $26^{\circ}\text{C} < \text{UTCI} \leq 32^{\circ}\text{C}$;
- No thermal stress: $9^{\circ}\text{C} < \text{UTCI} \leq 26^{\circ}\text{C}$;
- Slight cold stress: $0^{\circ}\text{C} < \text{UTCI} \leq 9^{\circ}\text{C}$;
- Moderate cold stress: $-13^{\circ}\text{C} < \text{UTCI} \leq 0^{\circ}\text{C}$;
- Strong cold stress: $-27^{\circ}\text{C} < \text{UTCI} \leq -13^{\circ}\text{C}$;
- Very strong cold stress: $-40^{\circ}\text{C} < \text{UTCI} \leq -27^{\circ}\text{C}$;
- Extreme cold stress: $\text{UTCI} < -40^{\circ}\text{C}$.

2.8. Tree-Related Simulations

The potential ecological effects of deciduous broadleaf trees were analyzed for two phases: the initial planting phase (T_0) and the 10-year post-planting scenario (T_{10} , i.e., the ex-post scenario). It was assumed that, by T_{10} , trees would reach their projected height, modeled under ex-post summer and winter scenarios. Simulations of tree effects were conducted using the i-Tree Eco software, incorporating project-specific data on species, canopy dimensions, diameter at breast height, total height, and land use.

The morphological characteristics modeled for the 10-year post-planting scenario (average height of 9 m and average canopy diameter of 7 m) are not arbitrary. They are based on established growth rates for Mediterranean urban climates and species-specific municipal databases. The 87 newly introduced trees comprise species carefully selected for their growth suitability in Florence's urban context:

- High-growth/large-crown species such as *Platanus × acerifolia*, *Celtis australis*, and *Quercus robur* were projected to reach a height of 12 m and a crown diameter of 10 m after 10 years;
- Medium-to-low growth species like *Cercis siliquastrum* were conservatively modeled with a height of 4 m and a canopy diameter of 3 m. These dimensions represent conservative, medium-term growth stages rather than full maturity, ensuring that the 10-year projection (T_{10}) remains highly realistic and not overly optimistic.

The i-Tree Eco software suite uses a scientifically robust methodology to quantify the environmental benefits of urban forests and individual trees [36]. By integrating local data and extensive tree growth databases, i-Tree Eco provides precise insights into the ecological benefits of trees to support sustainable urban planning and environmental management. In this study, the following elements were estimated:

- Gross carbon sequestration (kg C/year): quantifies the amount of elemental carbon sequestered annually by plants through biomass growth. It is estimated by integrating tree inventory data with growth models, accounting for species-specific growth rates and local environmental conditions, enabling accurate assessments [26];
- Total pollutant removal (kg/year): represents the estimated amount of the atmospheric pollutants included in the analysis that are removed by trees. This is achieved through models that consider leaf surface area, local pollution concentrations, and meteorological data [26]. The calculation includes nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter at 2.5 microns and 10 microns ($\text{PM}_{2.5}$ and PM_{10}). The pollutant removal estimation was based on historical air quality monitoring data from the year 2015, recorded by an institutional monitoring station in Central Florence. The selection of this specific baseline year was dictated by the strict data requirements of the i-Tree Eco model, which demands synchronized, continuous, and gap-free hourly meteorological and environmental recordings for an entire calendar year to compute dry deposition and canopy removal algorithms. The 2015 dataset represents the most complete, robust, and officially validated hourly baseline available for the Florence urban area within the i-Tree database. Furthermore, the primary objective of this simulation is to quantify the relative biological removal capacity and ecological performance of the vegetation over a 10-year growth horizon (comparing T_0 and T_{10}) under typical urban pollution loads, rather than providing an absolute, real-time forecast of current ambient air concentrations. However, due to the absence of sulfur dioxide (SO_2) and ozone (O_3) measurements in the validated baseline dataset, these pollutants were excluded from the overall estimate. Therefore, the reported pollutant-removal values should be interpreted as partial estimates limited to NO_2 , CO, $\text{PM}_{2.5}$ and PM_{10} ;
- Potential evapotranspiration (m^3/year): accounts for the combined evaporation from the soil and transpiration from plants under the assumption of unlimited water availability. It is determined using species-specific parameters and local climate data, reflecting the water transpired by trees and evaporating from surrounding soil and surfaces [37];
- Oxygen production (kg/year): estimated as the net annual oxygen generation, which accounts for oxygen produced during photosynthesis minus the oxygen consumed through plant respiration [26,38]. It is directly correlated with the amount of carbon sequestered by trees, which is, in turn, related to the accumulation of biomass;

- Avoided runoff (m^3/year): calculated by assessing the capacity of tree canopies to intercept rainfall, thereby reducing the volume of stormwater that reaches the ground [26]. The estimates use the Leaf Area Index (LAI), calculated from leaf surface area in relation to tree characteristics such as species, total height, and diameter at breast height.

3. Results

The results of this study focus on an area centered around Artom Square, the site of the proposed intervention. The urban climate models have a horizontal and vertical spatial resolution of 1 m, covering an area of $180 \text{ m} \times 180 \text{ m}$, and a vertical extent of 30 m. For the results, the domain was reduced to $160 \text{ m} \times 160 \text{ m}$ to exclude data potentially affected by simulation edge errors.

3.1. Morphology and Urban Features of Ex-Ante and Ex-Post Scenarios

Morphological analysis is a fundamental preliminary step in urban planning, as it characterizes the physical features influencing the urban microclimate. This assessment is supported by digital elevation models, seasonal shadow patterns, and SVF maps (Figures S1–S3 in the Supplementary Materials). The square exhibits a flat and uniform elevation of 44 m a.s.l., while surrounding buildings range from 3 to 15 m in height and existing trees vary between 3 and 6 m in height. The DSP and SVF indicators revealed limited shading in both seasons (DSP = 0.63 in winter, 0.74 in summer; SVF = 0.8), confirming high solar radiation exposure.

Furthermore, this characterization phase allowed for a detailed quantification of land cover elements, building materials, albedo values, and vegetation features. The surrounding buildings have predominantly flat roofs made of bituminous conglomerates in shades of light-to-dark gray and black. Additionally, field surveys conducted on five paved sites within the square indicated an average asphalt albedo of 0.15. Across the five surveyed sites, ST decreased markedly as the albedo increased over the measured range (0.12–0.18). The relationship is clearly non-linear, being steeper at the low-albedo end. A second-order polynomial provided the best fit to the data ($R^2 = 0.95$) (Figure 2). This relationship is strictly descriptive of the local pavement materials and environmental conditions of the study area during the monitoring window. The homogeneity of the on-site paving materials, combined with the internal consistency of the measured albedo–surface-temperature relationship, supports the suitability of this sampling approach for the local, site-specific scope of the study.

In terms of vegetation, tree cover in the area is scarce, consisting mainly of three maples (*Acer saccharinum*) near the square, some poplars (*Populus nigra*) and pines (*Pinus pinea*) to the northeast, and linden trees (*Tilia × europaea*) planted along the street. This limited tree presence contributes to the overall low shading and high solar radiation exposure observed across the square.

The ex-ante and ex-post urban features and land cover are shown in Figure 3 and Table 1, respectively.

Table 1 shows that nearly 98% of the area is covered by dark asphalt surfaces with a low albedo of 0.15. The primary design elements of the proposed scenario include:

- The integration of 50% of drivable and pedestrian surfaces with high-albedo asphalt and concrete (0.35);
- The conversion of 12% of the area into semi-permeable parking spaces;
- An increase in shrubs and grass-covered surfaces from 2.1% to 37.4% of the study area;
- The addition of 87 new deciduous broadleaf trees, selected for their suitability to the local climate, urban growth conditions, and ecological and social functions, consistent with existing Florence species: *Platanus × acerifolia* and *Pyrus calleryana* account for

46% of the new plantings, alongside *Celtis australis* (17), *Cercis siliquastrum* (12), *Corylus colurna* (8), *Quercus robur* (5), *Acer campestre* (3), and *Salix alba* (2).

Table 1. Urban land cover quantification of the current condition (ex-ante) and design scenario (ex-post).

Urban Land Cover	Ex-Ante	Ex-Post
Low-albedo (asphalt) pavements (%) [m ²]	97.9 [5015.4]	-
Bush and grass surfaces (%) [m ²]	2.1 [108]	37.4 [1918.4]
High-albedo (asphalt/concrete) pavements (%) [m ²]	-	50.7 [2595.3]
Semi-permeable parking areas with grass grid and concrete blocks (%) [m ²]	-	11.9 [609.7]
Trees (number)	3	90

The percentage value refers to the surface area covered by the study area (Artom Square). The 90 trees in the ex-post scenario include the 3 pre-existing preserved trees plus the 87 newly introduced trees.

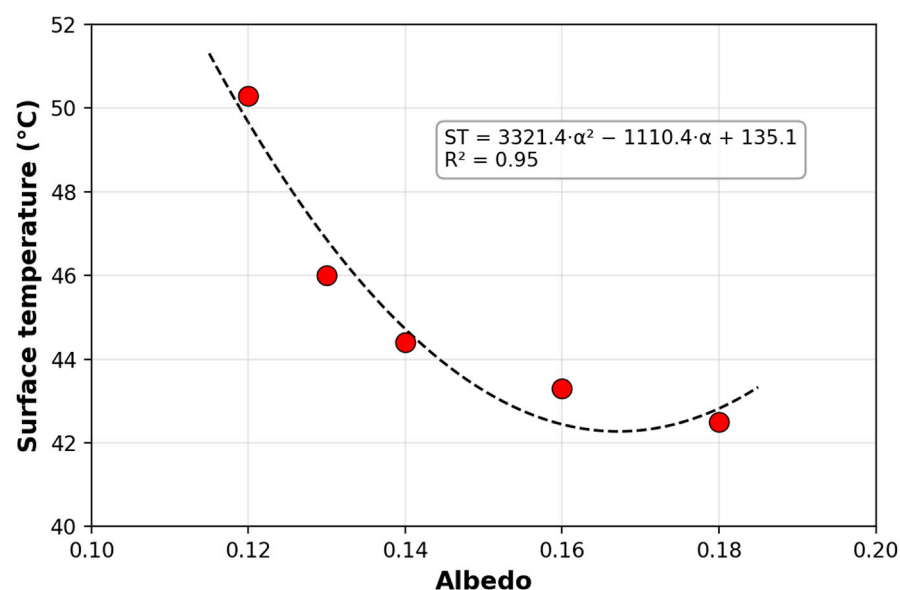


Figure 2. Relation between albedo and surface temperature (ST) measurements, recorded at five sites of the study area. The dashed line is a second-order polynomial fit to the five measured points ($ST = 3321.4 \cdot \alpha^2 - 1110.4 \cdot \alpha + 135.1$; $R^2 = 0.95$), shown as descriptive of the local paved surfaces and monitoring conditions rather than as a general relationship.

3.2. Study Area Modeling in ENVI-Met

Following the comparison procedures described in Section 2, the ENVI-met model simulations were first compared with the ERA5 boundary forcing for the two reference solstice days. The comparison showed a high degree of consistency, with an R^2 value of 0.98 and MAE (Mean Absolute Error) and RMSE (Root Mean Squared Error) values ranging from 0.3–0.4 °C in winter to 1.1–1.6 °C in summer, broadly consistent with the values reported in previous studies [20,39,40]. However, because ERA5 data are also used to prescribe the meteorological boundary forcing, this comparison should not be interpreted as an internal consistency check, indicating that the ENVI-met simulations adequately reproduce the prescribed meteorological conditions without appreciable numerical drift. Further details are provided in the Supplementary Materials (Figure S4).

As ERA5 also provided the boundary conditions, this comparison is best interpreted as an internal consistency check confirming that the model reproduces its forcing without appreciable drift, rather than as an independent validation. An independent evaluation was therefore performed against the near-surface air-temperature observations from the AirQino monitoring station, located approximately 10 m from the study area, which

reproduced the observed diurnal cycle well ($PCC = 0.9$ in summer and 0.7 in winter; mean bias (ERA5 – AirQino) -3.0 °C in summer and -2.0 °C in winter; RMSE 3.9 °C in summer and 3.4 °C in winter; MAE 3.1 and 2.7 °C, respectively).

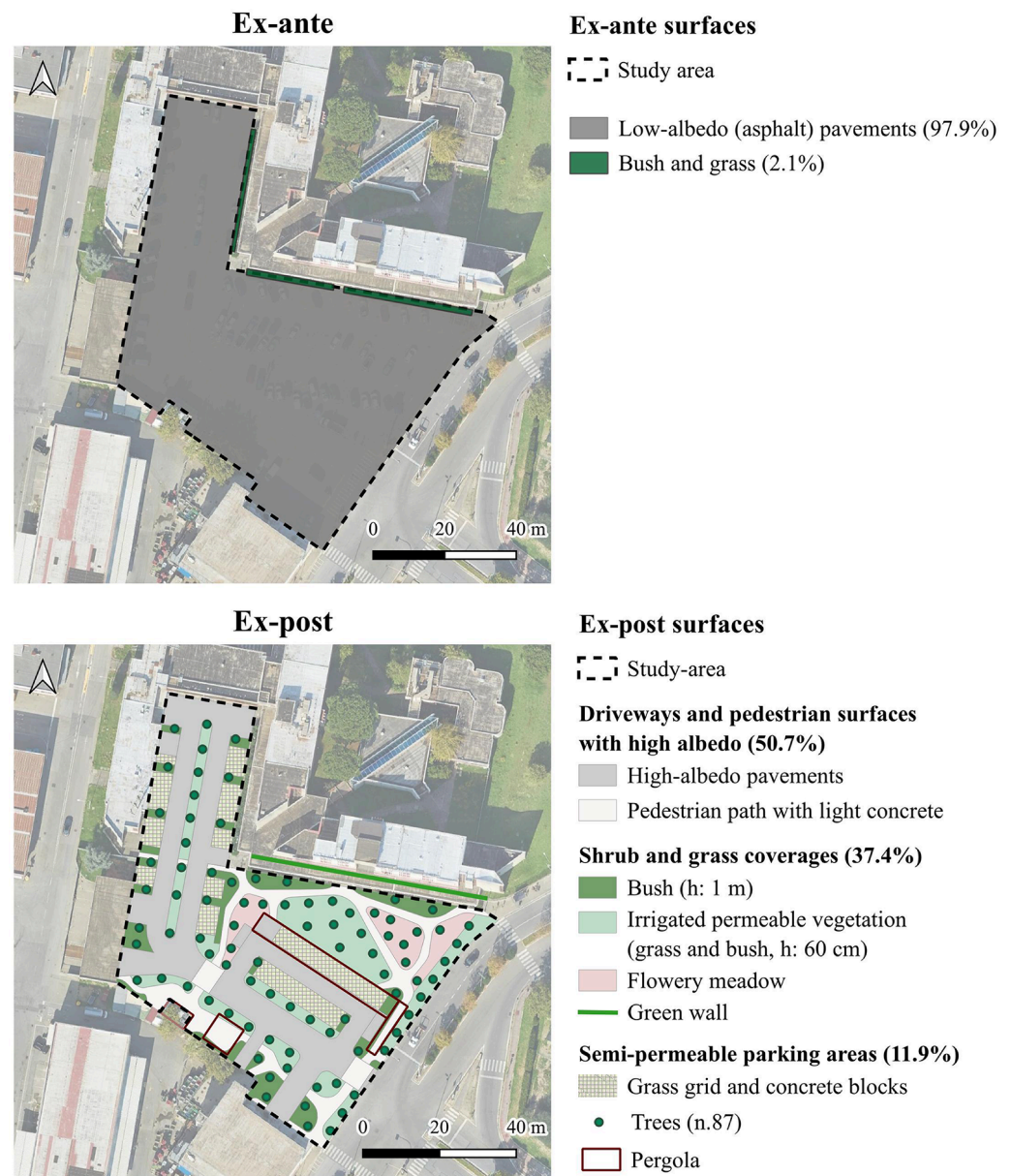


Figure 3. Urban surface coverage in the current (ex-ante) and design (ex-post) scenarios.

As a further independent check on the simulated surface temperatures—the variable driving the study’s largest reported effect—the FLIR measurements at the five survey points (Section 2.4) were compared qualitatively with the simulated ex-ante ST at midday. The FLIR/albedo survey (solar noon, 10 May 2024) and the ex-ante simulation (summer solstice, 21 June 2023) do not coincide in date, and the FLIR, ENVI-met and Landsat-8 sources differ in spatial resolution (point/sub-meter, 1 m and ~ 100 m resampled to 30 m, respectively). The comparison is therefore a cross-check of magnitude rather than a co-located, point-by-point validation. Within this scope, across the five points, the FLIR-measured ST (mean 45.3 °C, range 42.5 – 50.3 °C) and the simulated ex-ante ST (mean 49.0 °C, range 48.1 – 50.0 °C) fell within the same midday range, with the simulation slightly warmer on average (mean bias $+3.7$ °C, MAE 4.4 °C, RMSE 4.8 °C). Both sources thus place the low-albedo asphalt in the same high surface-temperature band, consistent with the ≈ 50 °C summer-noon values

derived from Landsat-8 for this hot spot (Section 2.1.1). The agreement is therefore one of magnitude rather than of the point-by-point ranking. The two datasets are not significantly correlated across the five sites (Pearson $r = -0.30$, $p = 0.63$), which is expected given the small sample ($n = 5$), the non-coincident acquisition dates, and the contrasting spatial supports. The 1 m ENVI-met field is comparatively homogeneous over the near-uniform asphalt (range 1.9 °C), whereas the point-scale FLIR readings capture finer material and micro-shading variability (range 7.8 °C). This qualitative cross-check therefore supports the simulated magnitude of the ex-ante surface temperatures rather than their fine-scale spatial pattern.

The 3D ex-ante and ex-post models (Figure 4) exhibit a complex structure, integrating multiple datasets that quantitatively describe the urban and climatic characteristics of the study area. These datasets include the geometry of surfaces and volumes, the albedo and emissivity of materials, the Leaf Area Density (LAD) of vegetation, and hourly climatic conditions for the selected period.

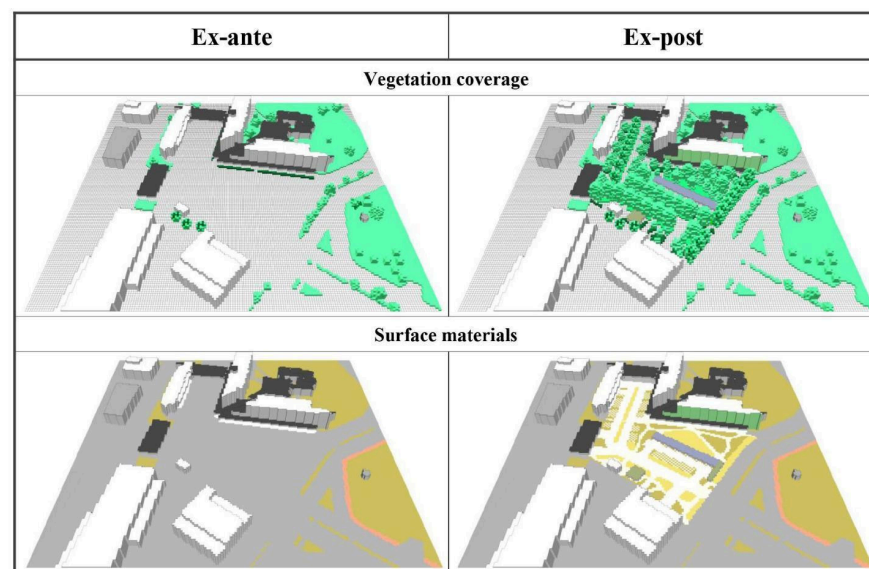


Figure 4. Ex-ante and ex-post three-dimensional ENVI-met models: focus on vegetation coverage and surface materials. In the vegetation coverage panels, light green indicates low vegetation/grass and dark green indicates trees; white and grey volumes represent buildings. In the surface material panels, grey indicates asphalt; light red indicates the red-asphalt cycle path; ochre indicates the existing permeable soil; pale yellow indicates the new permeable pavements of the green-blue infrastructures; flat white surfaces indicate high-albedo pavements; white and grey volumes represent buildings.

Figure 4 shows the main features of the ENVI-met model: ex-ante and ex-post surface materials and vegetation (tree and grass) cover. Table 2 summarizes the main meteorological parameters used in the summer and winter simulations, showing the average values recorded on June 21st and December 22nd of 2023.

Table 2. Average values of the summer and winter meteorological datasets: air temperature, relative humidity, wind speed and direction, and precipitation.

Meteorological Parameter	Summer	Winter
Air temperature (°C) at 2 m above ground [min–max]	26.4 [18.1–31.6]	9.8 [7.3–13.2]
Relative humidity (%) [min–max]	54.1 [37.0–78.0]	90.0 [70.0–90.0]
Wind direction (°) and speed (m/s) at 10 m above ground	163.7/2.1	169.3/2.2
Precipitation (mm)	0.0	0.0

3.3. Urban Seasonal Thermal Indicators

The following subsections present the spatial thermal results in detail: hourly day/night distributions of ST, T, and UTCI for summer and winter (Figures 5 and 6), the corresponding hourly ex-ante/ex-post difference maps (Figures 7 and 8), the per-surface-type thermal response (Table 3), and the fraction of the study area within each UTCI stress class (Supplementary Tables S3 and S4). Complete hourly values and full simulation outputs are provided in Supplementary Table S2 and Figures S5–S10, and all maps are available for interactive inspection through the online Google Earth Engine application.

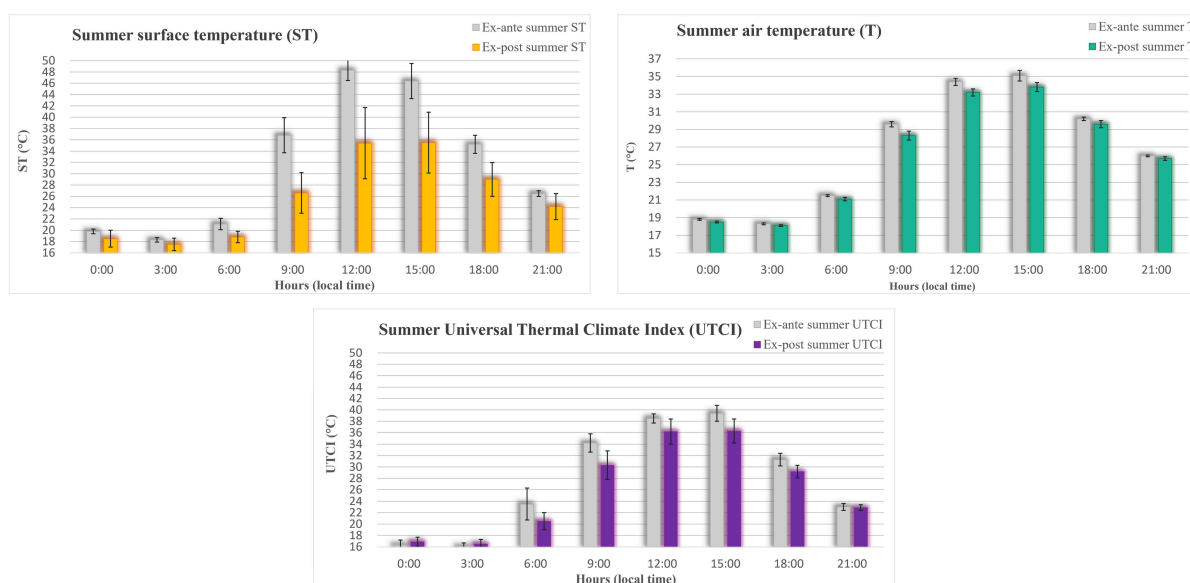


Figure 5. Hourly distribution of thermal indicators under ex-ante and ex-post scenarios in summer (21 June 2023): surface temperature (ST), air temperature (T), and Universal Thermal Climate Index (UTCI).

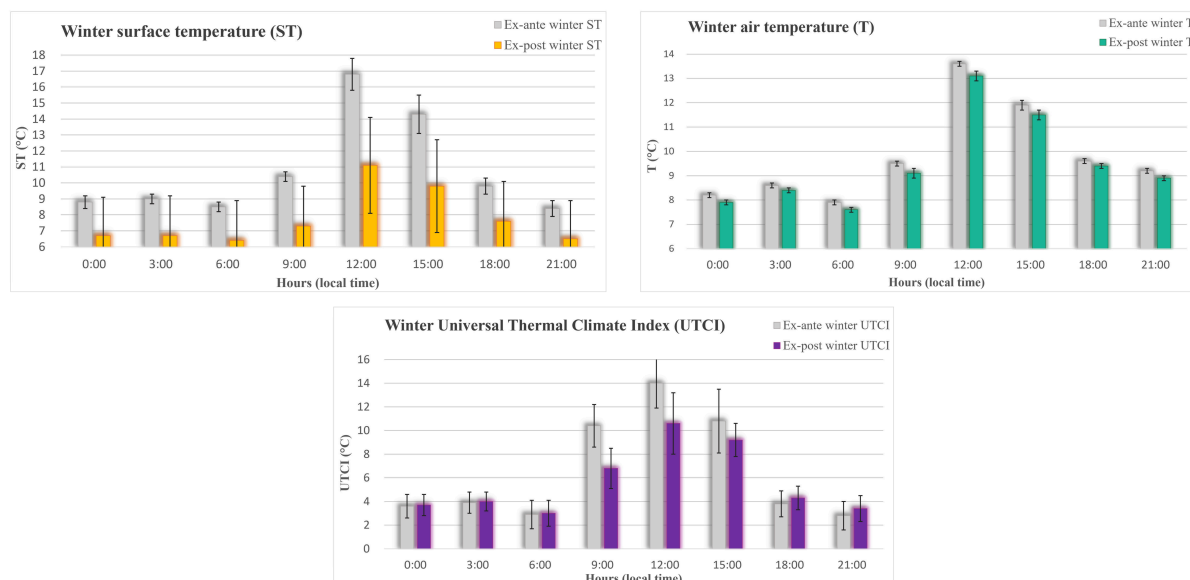


Figure 6. Hourly distribution of thermal indicators under ex-ante and ex-post scenarios in winter (22 December 2023): surface temperature (ST), air temperature (T), and Universal Thermal Climate Index (UTCI).

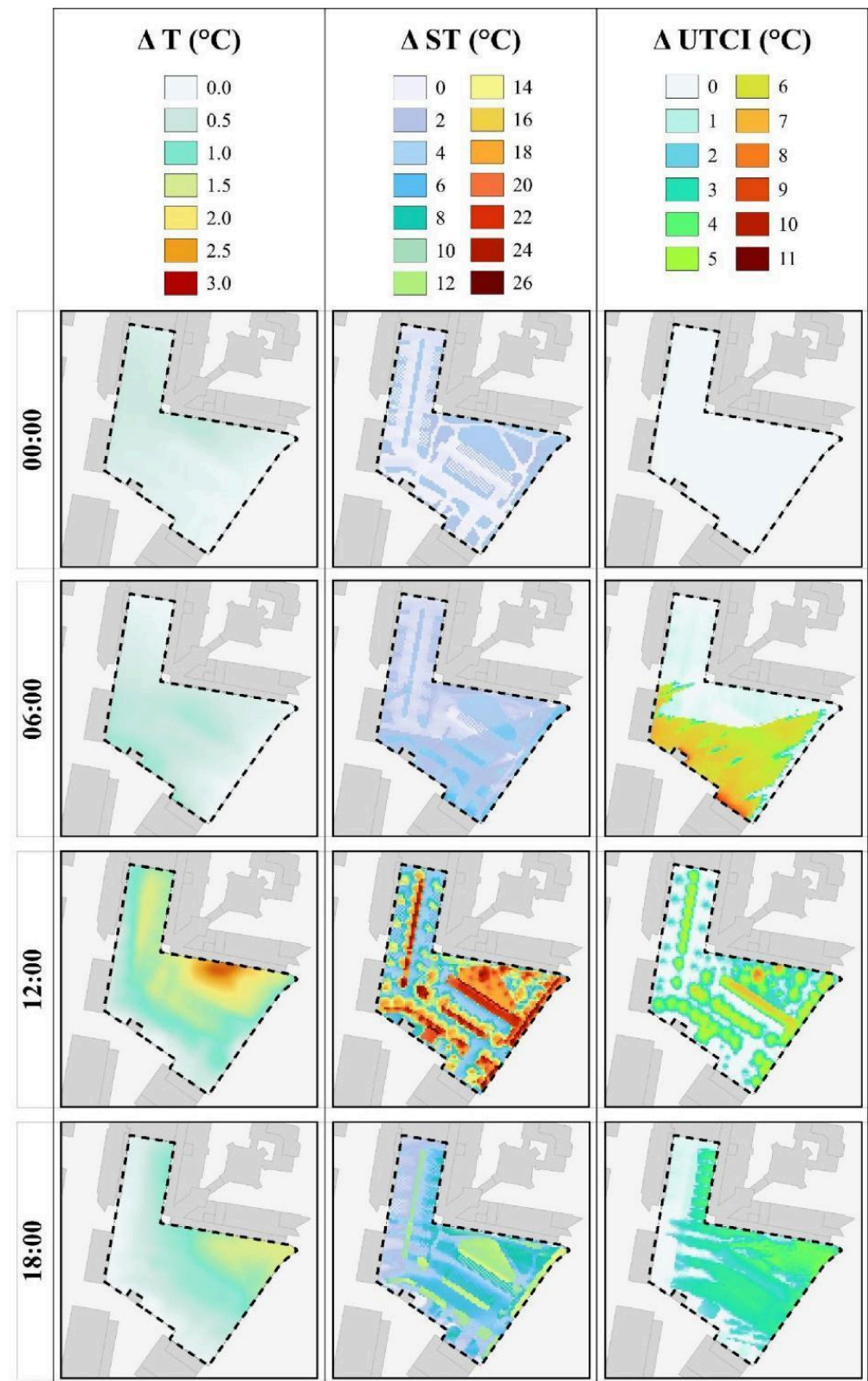


Figure 7. Hourly thermal differences simulated between the ex-ante and ex-post scenarios, in summer (21 June 2023) from 0:00 to 18:00: ΔT (air temperature difference at 1.5 m height), ΔST (surface temperature difference), and $\Delta UTCI$ (Universal Thermal Climate Index difference at 1.5 m height).

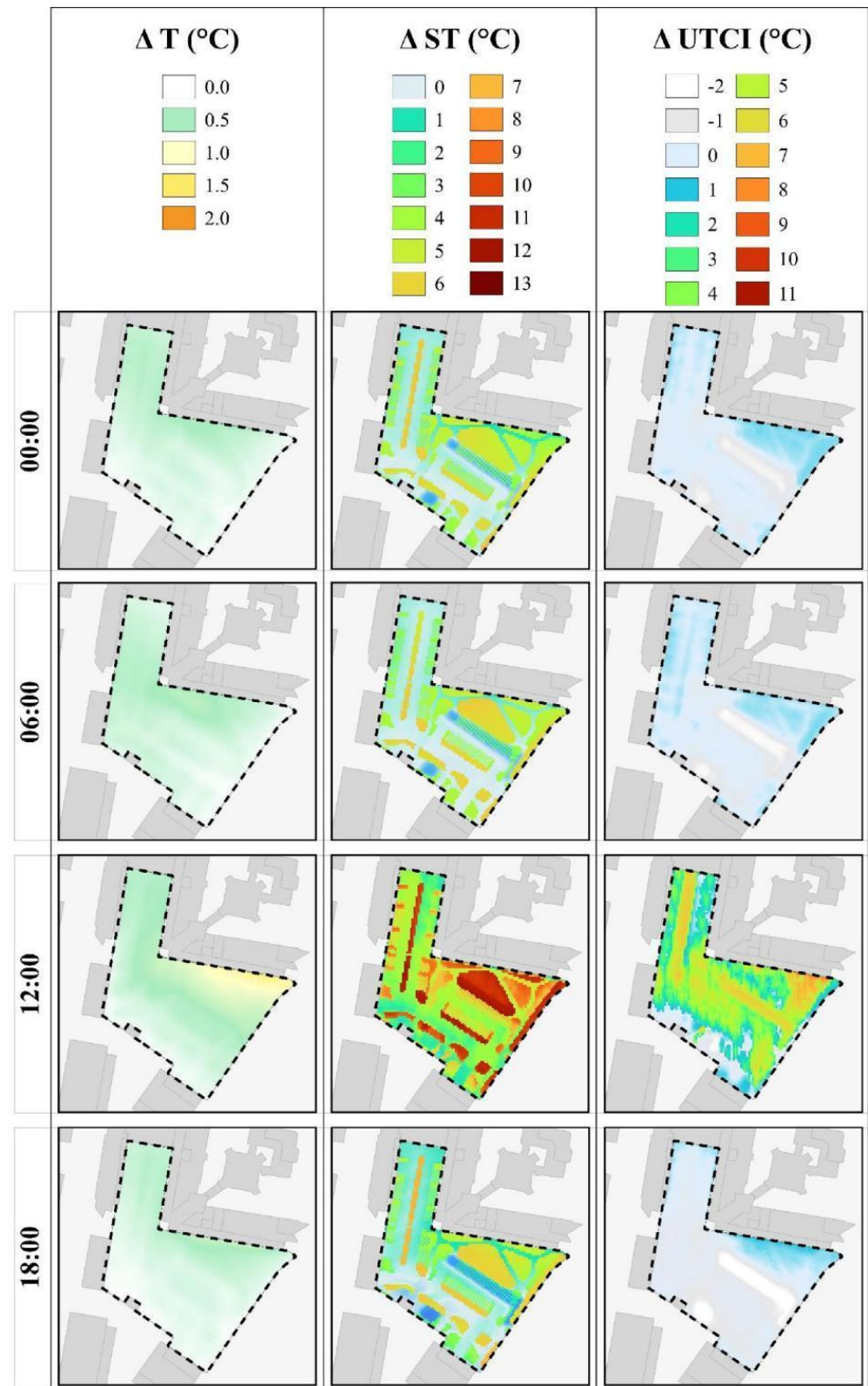


Figure 8. Hourly thermal differences simulated between the ex-ante and ex-post scenarios, in winter (22 December 2023) from 0:00 to 18:00: ΔT (air temperature difference at 1.5 m height), ΔST (surface temperature difference), and $\Delta UTCI$ (Universal Thermal Climate Index difference at 1.5 m height).

Table 3. Average air temperature (T) and surface temperature (ST) variations between impermeable and bush surfaces in the ex-post simulation compared to the ex-ante.

Simulation	Surfaces	T (°C)	ST (°C)
Ex-ante	Low-albedo (asphalt) pavements	34.4	56.8
Ex-post	High-albedo (asphalt/concrete) pavements	33.4	37.4
Δ		−1.0	−19.4
Ex-ante	Low-albedo asphalt pavements	34.4	56.8
Ex-post	Semi-permeable parking areas with grass grid and concrete	33.3	36.2
Δ		−1.1	−20.6
Ex-ante	Bush surfaces	34.0	40.9
Ex-post	Humid grass and bush surfaces (bioswale and rain garden)	33.1	27.1
Δ		−0.9	−13.8

The simulation results are spatial thermal indicators (raster data) representing hourly average values of atmospheric and surface thermal variations in ex-ante and ex-post scenarios. Using QGIS and R software, the following indicators were analyzed within the study area (the urban open space) at 1 m spatial resolution: surface temperature (ST), air temperature (T) and Universal Thermal Climate Index (UTCI). T and UTCI were extracted at 1.5 m above ground level to represent the climatic conditions experienced by pedestrians. Eight representative hourly thresholds from two days, the Summer (21 June 2023) and Winter (22 December 2023) solstices, were selected, covering both daytime and nighttime from 00:00 am to 9:00 pm.

A detailed analysis of the summer and winter simulations for ex-ante and ex-post conditions is provided in Figures 5 and 6, illustrating variations in diurnal and nocturnal thermal patterns across six selected periods, corresponding to the output maps shown in Figures 7 and 8. These maps depict the thermal conditions at four hourly intervals, spanning diurnal and nocturnal periods with a 6 h resolution from 00:00 am to 9:00 pm, during the Summer Solstice (21 June 2023) and Winter Solstice (22 December 2023). Each simulation output is provided in the Supplementary Materials (Figures S5 and S6). Further details of hourly thermal indicators (average, minimum and maximum values) are in the Supplementary Materials (Table S2).

All thermal indicator maps can be visualized in the Google Earth Engine App (Google Earth Engine, 2026: <https://ee-giuliaguerri.projects.earthengine.app/view/microclimate>, accessed on 17 September 2026).

Considering the differences in mean temperature between the ex-post and ex-ante conditions of the summer simulations, the following observations were made:

- T decreased by an average of 0.7 °C, with a maximum reduction of 1.3 °C between 9:00 am and 3:00 pm. The lowest values (0.2 °C) were observed during the nighttime (between 9:00 pm and 3:00 am);
- ST decreased by an average of approximately 6 °C, with the maximum reduction (nearly 13 °C) occurring at 12:00 pm during the daytime, and the minimum recorded at 3:00 am during the nighttime (0.8 °C);
- UTCI showed an average decrease of 1.6 °C, ranging from a minimum of 0.1 °C at night to a maximum of nearly 4 °C at 9:00 am during the day. A reduction in thermal stress was observed, with the index shifting from the “strong” to “moderate” level at 9:00 am and from “very strong” to “strong” between 12:00 pm and 3:00 pm.

The quantification of the percentage of the study area affected by thermal stress levels is detailed in the Supplementary Materials (Tables S3 and S4). This spatial data allowed for

a detailed evaluation of the thermal behavior of urban surfaces, enabling the identification of the areas most affected by the thermal benefits anticipated in the design phase.

Winter temperature differences between the ex-ante and ex-post conditions were less pronounced than in summer, with average T and ST reductions of 0.3 °C and 3.8 °C, respectively, and maxima of 0.5 °C and 5.7 °C at 12:00 pm. This measurable cooling response was also reflected in the UTCI classification, with an increased extent of “slight cold stress” under ex-post conditions at selected daytime hours, affecting approximately 76% and 85% of the square, respectively (Table S4). Overall, the winter simulations therefore indicate a modest thermal trade-off associated with the proposed summer cooling interventions.

Conversely, summer simulations revealed significant thermal improvements. “Strong” and “very strong thermal stress” were reduced by 50–60% in relative terms, particularly at 9:00 am, 12:00 pm and 3:00 pm. Peak temperatures at 12:00 pm highlighted maximum benefits in irrigated vegetated areas (bioswales and rain gardens), shrub-covered zones, and tree canopies, with ST reductions of 16–20 °C (Figure 7). Overall, T decreased by up to 1.3 °C and surface temperature by 13 °C between 9:00 am and 3:00 pm, while thermal stress dropped from “very strong” to “strong” (Figures 5 and 7).

In addition, T and ST of each surface type in the ex-ante and ex-post scenarios were analyzed at 12:00 pm during summer to assess potential thermal benefits associated with land cover (Table 3). Table 3 shows the T and ST values recorded on the ex-ante and ex-post surfaces, along with the related differences between each surface, calculated as the *ex-ante* minus the ex-post values (Δ). ST differences between the current and proposed scenarios ranged from 13.8 °C to 20.6 °C for bush and impermeable surfaces, while the T and ST differences between low-albedo asphalt surfaces (ex-ante) and high-albedo impermeable surfaces (ex-post) were approximately 1 °C and nearly 20 °C, respectively. Slightly higher differences were observed when comparing dark asphalt surfaces with semi-permeable parking areas featuring grass grids made of concrete blocks.

3.4. The Potential Tree Benefits in Ex-Post Scenario

This section summarizes the estimates of the ex-post simulations carried out in i-Tree Eco software [26], considering the initial planting phase (T_0) and the 10-year post-planting scenario (T_{10}). The selected parameters are collected in Table 4.

Table 4. Environmental ecological parameters of trees referring to the initial planting phase (T_0) and to the 10-year post-planting scenario (T_{10}).

Parameters	T_0	T_{10}	% Change
Canopy cover (m ²) [%]	544.8 [10.6]	1612.3 [31.5]	195.9
Gross carbon sequestration (kg C/year)	51.4	116.3	126.3
Total pollutant removal (kg/year)	1.1	3.8	245.5
Potential evapotranspiration (m ³ /year)	165.3	519.4	214.2
Oxygen production (kg/year)	135.4	307.4	127.0
Avoided runoff (m ³ /year)	0.96	3.3	243.8

Percentage values of canopy cover refer to study area coverage.

The gross carbon sequestration values double from T_0 to T_{10} , underscoring the ability of urban vegetation to act as a carbon sink and contribute to climate change mitigation. A comprehensive assessment of the hydrological benefits of urban trees, based on potential evapotranspiration, highlights their cooling effects. This estimate, along with oxygen production, represents the key benefits of urban trees. Compared to T_0 , these parameters double, reaching 500 m³/year for evapotranspiration and 307 kg/year for oxygen production in T_{10} . Additionally, avoided runoff increases threefold, reaching approximately 3300 L in T_{10} , emphasizing the role of urban trees in mitigating flooding and alleviating

pressure on stormwater management systems. In terms of pollutant removal, urban trees are estimated to remove 4 kg/year by T_{10} , particularly nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter ($PM_{2.5}$ and PM_{10}).

4. Discussion

This study shows that combining vegetation and high-albedo surfaces can effectively counteract surface positive thermal anomalies, even within constrained, semi-central open public spaces in historic cities. Focusing on Artom Square in Florence, a high-exposure site with extensive thermal hot spots [20] and an open-space morphology ($SVF = 0.8$) [41], the research highlights the local cooling and environmental benefits of integrated GBGI. Targeted interventions in dense urban contexts, where large-scale strategies are limited, are particularly valuable for enhancing microclimatic conditions and advancing sustainable urban goals in historic cities [42–44].

The proposed GBGI interventions in the ex-post scenario were identified as highly effective urban cooling strategies [8], providing additional benefits such as supporting urban biodiversity, enhancing ecological connectivity, and promoting residents' well-being [45,46]. The design integrated blue–green elements, including 87 deciduous broadleaf trees, bushes, and permeable ground vegetation such as rain gardens and bioswales, together with high-albedo pavements (51% of the square) to reduce heat absorption. Summer shading was further enhanced by deciduous broadleaf tree canopies and two pergolas, carefully positioned in central sun-exposed areas and along pedestrian paths to maximize cooling while maintaining access for vehicles. In addition, trees with large crowns were selected for their efficiency in cooling larger areas, and the overall layout was optimized to enhance daytime thermal comfort in open spaces, consistent with previous studies [41,47]. The proposed design also included 37% permeable green surfaces (grass, bushes and flowery meadows), and 12% semi-permeable pavements (such as green parking areas with grass cover), combining natural and reflective elements for synergistic cooling effects. The cool pavements, with an average albedo of 0.35 (representing a 133% increase from the ex-ante value of 0.15), comply with the Italian Ministry of the Environment and Energy Security's 2024 decree (National Decree of 5 August 2024), which sets a minimum albedo of 0.29 for pedestrian areas, sidewalks, squares, and cycle paths to improve thermal comfort, air quality, and ecological performance.

4.1. Integrating Green–Blue–Grey Infrastructures (GBGI) into Urban Spaces

Our findings show that the combined use of high-albedo pavements, green elements (trees and bushes), and irrigated permeable surfaces resulted in maximum reductions of 1.3 °C in T and 13 °C in ST between 9:00 am and 3:00 pm, substantially enhancing outdoor thermal comfort.

These results can be attributed to several factors that collectively contribute to the outcomes observed:

- The simultaneous presence of deciduous broadleaf trees and pergolas significantly reduces radiation and surface heating through shading [9,48];
- High-albedo pavements and green walls minimize solar absorption and heat buildup on facades and pavements [10,49];
- Vegetation elements, especially trees, bushes, grass surfaces, and flowery meadows, enhance cooling through evapotranspiration [8];
- Blue–green components, such as bioswales and rain gardens, leverage the high thermal capacity of water to improve local thermal conditions while offering multiple ecological functions [9,50].

The results confirm that combining vegetation with reflective surfaces may provide greater cooling benefits than either strategy alone, consistent with previous studies reporting daytime T reductions of up to $3\text{ }^{\circ}\text{C}$ [8,11,49]. This potential synergy combines the cooling benefits of evapotranspiration with the reduction in solar heat absorption achieved through higher surface albedo [11,51]. Beyond this synergy, the on-site measurements further illustrate how the cooling benefit varies with surface reflectivity. The albedo–surface-temperature relationship (Figure 2) is steeper at the low-albedo end, suggesting that, within the conditions examined, the largest reductions in surface temperature may be achieved by prioritizing the darkest, lowest-albedo asphalt surfaces. This observation may support a phased retrofitting strategy in settings where budgets or available space are constrained [8,10]. However, this interpretation should be treated cautiously. The polynomial fit in Figure 2 is based on only five co-located point measurements collected under a single set of clear-sky, dry, near-noon conditions and is therefore descriptive and site-specific rather than representative of a transferable quantitative albedo–temperature relationship. Pavement surface temperature is also influenced by thermal admittance, moisture content, ageing and soiling, as well as incident radiation and convective heat exchange. Consequently, equal changes in albedo do not necessarily produce equivalent changes in surface temperature across materials or sites. Accordingly, the relationship is used here only qualitatively to identify potentially high-priority surfaces for intervention, rather than as a predictive model.

However, increased reflectivity also entails an important trade-off. While cool pavements can substantially reduce surface temperature, the reflected shortwave radiation may increase radiant exposure at the pedestrian level, potentially offsetting part of the thermal benefit associated with lower surface temperatures [10,11]. Tree canopies provide a complementary mechanism by reducing the mean radiant temperature through shading while also contributing to cooling via evapotranspiration [8,9]. The proposed design therefore exploits the complementarity between reflective surfaces and vegetation rather than relying on reflectivity alone, consistent with the UTCI improvements reported in Section 3.3.

In this study, the proposed strategies reduced summer daytime T by an average of $0.7\text{ }^{\circ}\text{C}$, with the maximum reductions reaching $1.3\text{ }^{\circ}\text{C}$ during daytime hours, particularly in areas featuring a combination of irrigated, permeable vegetated surfaces, trees, bushes and green walls. Consistent with previous research [11], while vegetation or cool materials alone reduce T by $\sim 1\text{ }^{\circ}\text{C}$, their combined use achieves greater reductions ($\sim 2\text{ }^{\circ}\text{C}$), highlighting the enhanced cooling potential of integrated strategies. Similarly, Kumar et al. [8] identified the integration of street trees, ground-level vegetation, and water elements as the most effective strategy for reducing heat stress and enhancing human thermal comfort. Specifically, linear green features (street trees and bushes) and permeable paving solutions can reduce T by $\sim 3.8\text{ }^{\circ}\text{C}$ and $3.3\text{ }^{\circ}\text{C}$, respectively. These cooling effects are further amplified by blue–green infrastructures, including bioswales and rain gardens [8,11,50]. In addition to thermal benefits, such solutions also contribute to stormwater management and provide ecological benefits [52].

In the Florence case study, the comparative analysis of the ex-post and ex-ante scenarios demonstrated that the proposed interventions effectively mitigated extreme summer heat together with a smaller but detectable winter cooling effect. This indicates that the desired summer cooling does not compromise mild winter temperatures. In line with previous findings [11], the greatest reductions in air and surface temperatures occurred during daytime (between 9:00 am and 3:00 pm), with maximum decreases of $1.3\text{ }^{\circ}\text{C}$ in T and $13\text{ }^{\circ}\text{C}$ in ST in summer, and $0.5\text{ }^{\circ}\text{C}$ and $5.7\text{ }^{\circ}\text{C}$ in winter, respectively. These measures reduced summer daytime thermal stress by one level, shifting from “very strong” or “strong” to “moderate” heat stress, while in winter, they produced a modest thermal trade-

off, with an increased extent of “slight cold stress” at selected daytime hours. Moreover, peak reductions observed around noon underscore the effectiveness of the interventions in enhancing thermal comfort during the most critical summer hours. The 87 newly planted trees demonstrated notable ecological and environmental benefits, even within a relatively small urban area, including the annual removal of ~4 kg of pollutants, the production of 300 kg of oxygen, the sequestration of 116 kg of gross carbon, and a reduction in urban runoff by about 3 m³ per year. These results demonstrated how even small urban reforestation interventions can substantially enhance microclimate and ecological conditions, supporting findings from previous studies [26].

Moreover, the simulated microclimate and environmental benefits reflect the expected medium-term scenario, approximately 10 years after planting. By that time, the average tree height is projected to reach 9 m (ranging from 4 m for *Cercis siliquastrum* to 12 m for *Celtis australis*, *Quercus robur*, and *Platanus × acerifolia*). The average canopy diameter is estimated at around 7 m, varying from 3 m (*Cercis siliquastrum*) to 10 m (*Celtis australis*, *Quercus robur*, and *Platanus × acerifolia*), with the overall ground-level tree canopy coverage slightly exceeding 30%. To more accurately depict this dynamic, the potential benefits of trees were quantified by considering their progressive growth over a ten-year horizon, allowing us to assess the actual improvements experienced by people living in the area in the short- to medium-term. The progressive growth of trees over ten years is expected to increase canopy cover from 10% to about 30%, boost gross carbon sequestration and oxygen production by ~120%, and raise potential evapotranspiration, total pollutant removal, and avoided runoff by over 200%.

These results underscore the substantial thermal benefits of targeted land cover and material interventions in high-exposure urban areas. However, potential modeling uncertainties should be considered (see Section 4.2).

From a feasibility standpoint, the cooling benefits simulated for the irrigated vegetated surfaces are conditional on adequate water availability. To this end, the proposed green–blue solutions—permeable pavements, rain gardens and bioswales—are designed to harvest and retain stormwater, supporting local soil-water availability and limiting reliance on external supply during the dry summer months. Because the present study focuses on the microclimatic and environmental performance of the design scenario, the irrigation demand was not quantified in detail. The redesign also addresses the site’s current function: Artom Square presently serves as a parking area for the adjacent Mercafir market. Rather than removing this function, the design converts part of the impervious asphalt into semi-permeable, grass-grid parking areas (11.9% of the study area) and, in agreement with the City of Florence, preserves vehicular access to the market while markedly increasing permeable, vegetated and shaded surfaces. This balances the reduction in sealed parking against the climatic, hydrological and ecological gains of the intervention.

4.2. The Role of Predictive Microclimatic Simulation in Proactive Urban Design

A key value of this study lies in its predictive, simulation-based approach to urban microclimate assessment, employing high-resolution, site-specific modeling to anticipate the thermal and environmental effects of proposed interventions before their physical implementation. Rather than representing a radical paradigm shift, this ex-ante modeling serves as an objective, evidence-based decision-support tool. It allows planners to evaluate and optimize landscape elements before physical resources are committed, helping to identify potential microclimatic underperformance or unintended localized warming effects. Our simulations demonstrate that these microclimatic benefits are highly localized. While surface temperatures (ST) decrease dramatically (by up to ~13 °C) directly under tree canopies and on high-albedo pavements, the resulting air temperature (T) reductions are

far more modest, averaging 0.7 °C with localized daytime peaks of 1.3 °C. This physical discrepancy underscores that microscale interventions, while highly effective for localized human thermal comfort (as evidenced by the shifting of UTCI heat stress levels), do not alter regional-scale atmospheric conditions. The transpirational and reflective cooling effects are physically bounded by rapid atmospheric mixing, wind-driven air exchange, and the influence of the surrounding unmitigated urban fabric.

By simulating seasonal and hourly thermal dynamics, the research quantifies how specific urban design choices, such as tree placement, pavement albedo, and green infrastructure distribution, affect local microclimatic conditions. The selected temporal and spatial resolutions enabled a detailed assessment of diurnal and nocturnal climatic conditions across summer and winter, ensuring summer cooling interventions do not compromise winter conditions. Results show that even relatively small-scale interventions can provide substantial thermal and ecological benefits if strategically planned and tested through simulation, avoiding underperforming or counterproductive measures. Relative to our previous application of ENVI-met to tree-based mitigation scenarios in an industrial area of Florence [20], the present study extends the framework by jointly assessing vegetation and high-albedo surfaces, integrating tree-related ecosystem services over a 10-year growth scenario, and explicitly examining the balance between summer cooling benefits and winter thermal effects. The integrated methodological framework, combining QGIS for urban morphology analysis, ENVI-met for detailed microclimatic simulations, and i-Tree Eco for ecological benefit modeling, offers a replicable toolset for municipalities to evaluate the climate performance of urban projects. A clear distinction should nonetheless be drawn between the transferability of the methodological procedure and the generalizability of the quantitative results. The workflow itself—morphological characterization, in-situ albedo and surface-temperature surveys, microclimatic simulation and ecosystem-service assessment—is portable and can be readily re-applied elsewhere; the specific magnitudes reported here, however, are conditioned by the local morphology, materials, meteorological forcing and design of Artom Square and should not be expected to reproduce identically under different urban geometries, climates or vegetation configurations.

The projected 10-year ecological benefits (such as a threefold increase in avoided runoff and doubled carbon sequestration) represent theoretical maximum capacities modeled under standard conditions. In practice, realizing these benefits is strictly contingent upon species survival rates, local soil moisture availability, and consistent municipal maintenance during the critical establishment phase.

4.3. The Use of QGIS and ENVI-Met Software in Supporting Urban Climate Research: Challenges and Limitations

Geographic Information System (GIS) tools and numerical simulation software, like QGIS and ENVI-met, are widely used by researchers and professionals to develop strategies to counteract urban hot spots and enhance outdoor thermal environments. This section outlines their key advantages, challenges, and limitations in climate-sensitive urban design.

ENVI-met performs high-resolution microclimatic simulations of surface-vegetation-atmosphere interactions [16], while QGIS provides a geospatial platform for environmental data management and spatial analysis. ENVI-met incorporates detailed physical and thermal parameters (e.g., albedo, emissivity, and vegetation traits such as leaf type and leaf area density) and includes a stomatal behavior model [53], simulating both plant impacts on microclimate and climatic feedback on vegetation [54]. It also dynamically models soil moisture and evapotranspiration processes, offering a comprehensive representation of microclimatic dynamics.

While microclimatic software (ENVI-met) and ecological benefit models (i-Tree Eco) do not dynamically simulate tree mortality or operational maintenance within their physics packages, these factors were central to our planning:

- All 87 trees were chosen from the official plant species list approved by the City of Florence, curated specifically to select species with high climate resilience, low mortality rates, and high compatibility with the local Mediterranean urban environment;
- The master plan was developed in close collaboration with the Department of Environmental Affairs of the City of Florence. The municipality will manage post-planting maintenance, including regular pruning, pest control, and emergency watering during the critical establishment phase. This is expected to keep the mortality rate very low (typically below 5% for municipally managed urban forestry projects in Florence). These planning measures reduce but do not eliminate the associated uncertainty, which is addressed explicitly among the study limitations (Section 4.4).

The integration of ENVI-met and QGIS enhances analytical capacity by combining spatial data on land use, vegetation, and urban morphology with microclimate modeling. This synergy allows researchers and urban planners to predict the impacts of specific interventions, such as introducing green infrastructure, altering building materials, or changing land use, on local thermal conditions. This integration exemplifies how environmental modeling and geospatial analysis can jointly address the complex challenges of urbanization and climate change. However, these methods demand high computational power, specialized data, and interdisciplinary expertise, highlighting the need for continued methodological advancement and professional training.

Despite their effectiveness in urban climate research, some challenges and limitations persist. A primary limitation is the dependency on high-quality input data. The accuracy of ENVI-met simulations strongly depends on the availability and quality of the input data (e.g., detailed urban morphology, vegetation characteristics, and surface materials), which are often incomplete or unavailable in urban contexts. Furthermore, the models do not fully account for anthropogenic activities, such as heat emissions from vehicles, energy use, and mechanical cooling [41,55,56].

Additional limitations include the absence of detailed soil data (humidity and initial temperature) and the use of default leaf area density values for trees, as predefined in the software. In addition, the cooling performance simulated for irrigated vegetation, bioswales, and rain gardens is conditional on adequate water availability. In the proposed design, permeable surfaces and blue–green elements are intended to enhance stormwater retention and local soil-water availability. Moreover, as noted in prior studies [57], ENVI-met tends to overestimate T values in shaded ground-level areas, potentially affecting result interpretation. Consequently, future research will include in-situ data validation, ex-post thermal pattern monitoring, and cost–benefit analyses of GBGI solutions to ensure their technical, economic, and social feasibility.

4.4. Study Limitations

A limitation of this study is linked to the use of ERA5 reanalysis data, which, due to its coarse spatial resolution (~27 km), may not fully capture fine-scale urban microclimatic variability. However, utilizing a globally standardized, publicly accessible, and robustly validated gridded dataset like ERA5 is a deliberate methodological choice aimed at maximizing the transferability and replicability of the proposed assessment framework [58]. This approach ensures that urban planners and researchers in other geographical contexts can readily deploy our workflow without being constrained by the absence of local municipal weather stations. To overcome the limitations of the coarse spatial resolution and guarantee site-scale accuracy, we integrated our analysis with local monitoring. Specifically,

our validation analysis with a nearby meteorological station (AirQino platform) confirmed the reliability of the boundary inputs, showing strong correlations in summer ($PCC = 0.9$) and moderate correlations in winter ($PCC = 0.7$). These findings demonstrate that, while global reanalyses provide a highly portable foundation for driving microclimate models, pairing them with local in-situ measurements remains an essential best practice to capture fine-scale urban environmental variability and ensure local model calibration. Additionally, the study focused on representative solstice days, capturing the maximum radiative contribution at Italian latitudes, however overlooking seasonal thermal lags. Future work will build on this foundation by incorporating more comprehensive in-situ measurements and seasonal mean values, as well as additional periods within each season, to further refine urban microclimatic modeling and assess the performance of landscape interventions across the full seasonal cycle.

A further limitation concerns the ex-post tree-cover scenario. The reported 10-year (T_{10}) ecological and microclimatic benefits were modeled under standard, non-water-limited assumptions using species-specific growth curves and should therefore be interpreted as plausible potential capacities rather than definitive predictions. Individual tree survival, differential growth rates, soil-water availability, long-term maintenance and interannual environmental variability were not varied through a formal sensitivity analysis, and neither ENVI-met nor i-Tree Eco dynamically simulates tree mortality or soil–water feedback. Although the species were selected from the municipal list for their climate resilience and are supported by a municipal maintenance plan expected to keep mortality low, the realized benefits remain contingent on these factors. A systematic sensitivity analysis of alternative growth, survival and irrigation trajectories, quantifying the variability of the projected benefits across scenarios, is identified as a priority for future work, together with post implementation in situ monitoring aimed at empirically constraining the residual uncertainty.

Furthermore, while the use of the 2015 air quality baseline was necessary due to database compatibility and completeness constraints in i-Tree Eco, we acknowledge that urban pollutant concentrations may have shifted in recent years. Future studies should explore coupling microclimatic simulations with updated regional air quality dispersion models to capture current emission trends.

5. Conclusions

This study highlights the benefits of Green–Blue–Grey Infrastructure in counteracting urban hot spots and improving environmental conditions in a public square in Florence. Significant cooling effects and environmental benefits were achieved through the integrated use of high-albedo pavements, deciduous broadleaf trees, bushes, permeable vegetated surfaces, and water features such as rain gardens and bioswales, complemented by artificial shading structures like pergolas. The combined interventions produced the greatest effects during summer, achieving maximum reductions in T ($1.3\text{ }^{\circ}\text{C}$) and ST (approximately $13\text{ }^{\circ}\text{C}$) between 9:00 am and 3:00 pm. Comparisons between ex-post and ex-ante scenarios showed a marked reduction in summer thermal stress, together with a smaller winter cooling effect. This represents a modest seasonal trade-off, including an increased extent of “slight cold stress” at selected daytime hours, rather than a complete preservation of the ex-ante winter thermal conditions. Urban vegetation demonstrated substantial environmental benefits over time, doubling carbon sequestration and evapotranspiration and tripling avoided runoff ten years after planting. These improvements, including pollutant removal (NO_2 , CO , and particulate matter), emphasize the vital role of urban trees in sustainable urban development and environmental resilience, particularly in air quality enhancement and stormwater management. In this case study, the combination of nature-based solutions and cool materials proved an effective strategy for a fully paved square, and the approach

appears particularly promising for historically dense Italian urban contexts where space and regulatory constraints limit large-scale planting. Confirming its benefits elsewhere would, however, require site-specific assessment.

A key takeaway is the utility of predictive, simulation-based assessments in guiding local urban design. By comparing ex-ante and ex-post conditions, the study demonstrates that forecasting microclimatic impacts is a highly practical method for assessing and comparing design scenarios prior to execution. This evaluation framework allows planners to optimize tree layouts, select appropriate albedo thresholds, and maximize human thermal comfort, offering actionable insights to enhance microclimate and improve urban biodiversity.

These findings derive from a single case study, two seasonal reference days, and a projected design scenario that has not yet been implemented or validated ex post. Accordingly, while the methodological framework is transferable and the qualitative direction of the effects is expected to hold, the specific thermal and ecological magnitudes reported should be regarded as indicative of the study site rather than as generally reproducible values. Ex-post monitoring of the implemented design remains necessary to confirm the simulated benefits.

Considering these findings, the main challenges in the coming decades for policy-makers and urban planners worldwide will be to adapt cities to manage heat stress and promote resilient, equitable, and healthy urban environments.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/app16199509/s1>: Table S1. The main ENVI-met setting parameters of the urban and vegetation coverages in the ex-ante and ex-post scenarios; Table S2. Daytime and nighttime thermal indicators during the Summer Solstice (21 June 2023) and Winter Solstice (22 December 2023); Table S3. Percentage values of the study area affected by the corresponding Universal Thermal Climate Index (UTCI) levels of summer thermal stress in the ex-ante and ex-post scenarios; Table S4. Percentage values of the study area affected by the corresponding Universal Thermal Climate Index (UTCI) levels of winter thermal stress in the ex-ante and ex-post scenarios; Figure S1. Digital models: Canopy Digital Surface Model (CDSM) and Building Digital Surface Model (BDSM); Figure S2. Average daily shadow pattern (DSP) in summer and winter; Figure S3. Sky View Factor (SVF) in summer and winter; Figure S4. Correlation between the ERA5 (x-axis) and simulated (y-axis) hourly data of air temperature (T) for winter and summer reference days (21 June 2023, and 22 December 2023); Figures S5–S7. Summer climate simulation outputs showing ex-ante, ex-post and difference (Δ) values of air temperature (T), surface temperature (ST) and Universal Thermal Climate Index (UTCI); Figures S8–S10. Winter climate simulation outputs showing ex-ante, ex-post and difference (Δ) values of air temperature (T), surface temperature (ST) and Universal Thermal Climate Index (UTCI). Additional supplementary materials can be downloaded on the Zenodo platform (<https://doi.org/10.5281/zenodo.14824174>, accessed on 17 September 2026).

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Abbreviations

The following abbreviations are used in this manuscript:

SVF	Sky View Factor
DSP	Daily Shadow Pattern
UHI	Urban Heat Island
SUHI	Surface Urban Heat Island
T	Air temperature
ST	Surface Temperature
UTCI	Universal Thermal Climate Index
GBGI	Green–Blue–Grey Infrastructure
LAD	Leaf Area Density
LAI	Leaf Area Index
Ex-ante	Current scenario
Ex-post	Design scenario

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