Building and Environment 245 (2023) 110854

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Urban microclimate simulations based on GIS data to mitigate thermal hot-spots: Tree design scenarios in an industrial area of Florence

Giulia Guerri, Alfonso Crisci, Marco Morabito *

Institute of Bioeconomy (IBE), National Research Council, 50019, Florence, Italy

ARTICLE INFO

Keywords:
Mitigation strategies
Thermal anomaly
Urban morphology
GIS tools
Nature-based solutions
Shading

ABSTRACT

Surface thermal hot-spot areas, and especially industrial and commercial areas, mainly characterized by high artificial surfaces and low vegetation coverages, consistently affect the livability in urban areas. In this study, one of the warmest areas of Florence (Italy), the main agri-food market was selected to perform three tree design mitigation scenarios: a) mitigation intervention by using 5-m high trees (T_5), b) intervention with 10-m high trees (T_{10}) and c) intervention alternating 5- and 10-m high trees ($T_{5\text{-}10}$). The methodology was based on the microclimate monitoring and simulation by urban characterization, involving open GIS data from different data sources by using spatial software tools (QGIS and the ENVI-met software). Thermal patterns (air Temperature, AT; Mean Radiant Temperature, MRT; Surface Temperature, ST; Universal Thermal Climate Index, UTCI) were simulated at 9 a.m. and 3 p.m. by the three scenarios and were then compared through a non-parametric statistical test with the ex-ante thermal situation. The results revealed that a 10% increase in the tree canopy on road surfaces had a significant impact on the thermal environment, showing the greatest effect at the surface level. The greatest cooling impact was observed during the afternoon (3 p.m.) considering the T_{10} three design scenario: MRT, ST and UTCI decreased by 6.0 °C, 4.1 °C and 1.7 °C respectively when compare to the ex-ante situation. These findings provide very useful information for urban planners and landscape architects to plan targeted interventions aimed at mitigating urban thermal anomalies in industrial areas.

1. Introduction

It was widely recognized that climate change has led to an increase in the level of risk for people, infrastructure, and nature due to the increase in magnitude and frequency of weather extremes [1]. Several natural ecosystems and economic sectors are exposed to related climate change phenomena, especially in built-up areas where human activities, land use, and high soil consumption levels affect the urban microclimate [2].

Urban areas, in particular industrial and commercial zones, are recognized as areas capable of negatively influencing the urban thermal pattern creating significant thermal hot-spot areas [3,4] because of high imperviousness and low reflectivity properties of materials, the absence (or very low presence) of vegetation and the anthropogenic heat emission from industrial sites.

It was widely demonstrated that soil consumption, defined as the change of land cover from natural to artificial areas to perform urban functions, is affecting our cities [2–6], and high imperviousness concentrations contribute to worsen the thermal environment, especially in the industrial and commercial areas [4]. A recent case study conducted on the city of Florence investigated the surface thermal hot-spot areas on industrial sites, where over 80% of impervious surfaces (including buildings and pavements) were detected [4].

The high thermal conductivity of construction materials and high levels of soil consumption increase the absorption of solar radiation, limits soil permeability, increase runoff, and reduce vegetation cover limiting evapotranspiration [5,6]. These urban characteristics can contribute to a microclimate up to 10 °C warmer in heavy industry areas than the surrounding rural areas [4,6], as confirmed by several studies involving the Urban Heat Island (UHI) phenomenon [7]. The UHI phenomenon, defined as higher temperatures in city areas as compared to surrounding rural areas, was widely recognized as a well-documented impact of urbanization, typically in highly built-up zones such as urban and industrial areas.

Elevated temperatures due to UHI effects affect the thermal comfort of humans and induce heat-related health problems, leading to heat strokes, respiratory difficulties, heat cramps, dehydration, and heat related-morality [1]. These impacts vary across different geographical regions and employment sectors. Workers engaged outdoor in activities from moderate to intense levels directly exposed to the sun are among

* Corresponding author. Institute of Bioeconomy, National Research Council, via Madonna del Piano, 10, 50019, Sesto Fiorentino, Florence, Italy.
E-mail address: marco.morabito@cnr.it (M. Morabito).

https://doi.org/10.1016/j.buildenv.2023.110854
Received 2 June 2023; Received in revised form 16 August 2023; Accepted 31 August 2023
Available online 28 September 2023

Abbreviations

AT	Air Temperature
CDSM	Canopy Digital Surface Model
DEM	Digital Elevation Model
DSM	Digital Surface Model
DSP	Daily Shadow Pattern
MRT	Mean Radiant Temperature
RH	Relative Humidity
SVF	Sky View Factor
SH	Shadow Hours
ST	Surface Temperature
WS	Wind Speed
WD	Wind Direction
UTCI	Universal Thermal Climate Index

the most exposed categories, as also demonstrated by recent publications on Italian agricultural and construction workers [8,9]. However, heat stress can determine significant problem also for industrial and commercial workers involved in semi-outdoor unventilated shaded areas, under covers, or still in indoor settings such as non-air-conditioned sheds or if the temperature levels inside factories are not regulated properly [10].

According to the International Labour Organization [10], heat stress is increasingly an obstacle to economic activity since it reduces the ability of business to operate during the hottest hours.

Since the effects of heat stress in urban areas have become more severe in the last decade, many countries have decided to implement national and local strategies for climate change adaptation and mitigation, including nature-based solutions (NBS), green and blue infrastructures (GBI), high-reflective materials for pavements, roads, and roofs [11]. Urban planners have to develop city models to reduce thermal stress impact on the urban environment, with particular attention to industrial areas as priority zones for heat mitigation strategies. Among the urban mitigation strategies, greenery has been regarded as one of the valid measures to have a significant cooling effect and provide better thermal comfort for urban dwellings [12,13].

The development of urban forestry and the application of vegetation provide better thermal comfort for urban dwellings by reducing the thermal stress from pavements during the day. Trees and vegetation provide direct shading to pavements, which also decreases pavement maintenance costs by reducing the rate of pavement deterioration. By increasing the quantity of vegetation or vegetation ratio, applying appropriate plant layout, and choosing the right vegetation species, the urban heat load can be alleviated efficiently [14,15]. Further research underlined the cooling effect of green space is closely related to coverage area, tree canopy size and coverage, average leaf area index (LAI) [16], and other landscape metrics useful to evaluate the geometry composition and configuration of land cover classes [17]. As a result, vegetation can counteract the effects of solar radiation by shading and evapotranspiration by trees, shrubs, and lawns that reduce local temperatures. In addition, it was widely demonstrated that urban trees can reduce energy demand effectively more than urban lawns due to their shading effect [16].

Recent studies [18] showed the effect of trees on urban mitigation, verifying that vegetation scenarios reduce air temperature by 0.5 K in built-up areas and enhance thermal performance (in terms of Physiological Equivalent Temperature, PET). Several studies have shown that urban microclimatic conditions are not only affected by vegetation and surface thermal properties of materials but also by physical properties regarding the urban morphology (surface fraction, building height, SVF, etc.), which affect local climate through their modification of airflow, atmospheric heat transport, shortwave, and longwave radiation balances [13,19,20].

A previous study [14] indicated that the cooling effect of urban trees is highly associated with the Sky View Factor (SVF) effect, showing that trees are more effective in low urban density (high SVF) than in compact urban areas (low SVF).

Global case studies have shown that scenario simulations employing techniques and microclimate environmental modeling software allow for the study of physical microclimate phenomena with great precision [21–27]. Among the most used software for microclimate modeling, the ENVI-met, a holistic three-dimensional microclimate model [28], has been widely used to assess vegetation thermal effect simulation [29,30]. Most studies were conducted in Asia and Europe, and in the temperate zone, and the vegetation effect combined by different GBI types was mostly investigated [31].

Through the ENVI-met software, it is possible to simulate the surface-plant-air interactions in a complex urban environment by using a detailed 3D-plant module and considering the plant evapotranspiration. The 3D-plant module enables the characterization of tree features in detail, like the tree height, the canopy shape, and the trunk height, also specifying the LAD and tree species (or simply defining deciduous and coniferous trees).

In this study, ENVI-met was used to simulate different tree design scenarios in an industrial and commercial area, an agri-food area located in the city of Florence (Italy), identified in a previous study [4] among the warmest in the Florentine area. In fact, this area is characterized by very strong heat stress during daytime (UTCI >38 °C) and significant positive surface thermal anomalies.

In this study, thermal stress was calculated for workers performing moderate activities, therefore concerning handling, transport, loading and unloading of material, driving vehicles for the movement of material and alternating direct exposures to the sun or in shady areas, under natural or artificial covers or in not air-conditioned halls. The selected area was located in a complex urban context where high imperviousness, low albedo pavement and vegetation surfaces contributed to modify the urban microclimate. This area was selected to perform three tree design mitigation scenarios with different characteristics:

a) mitigation intervention by using 5-m high trees, b) intervention with 10-m high trees and c) intervention alternating 5- and 10-m high trees. The thermal patterns obtained by the three scenarios were then compared with the ex-ante thermal situation.

The results of this study can provide very useful information for urban planners and landscape architects to plan targeted interventions aimed at mitigating urban thermal anomalies in building areas that are particularly strategic for the urban economy, but having a strong impact from a microclimatic and environmental point of view, such as industrial sites.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) is located in the municipality of Florence (central Italy) and it was identified on the basis of a recent study [4] which selected this area as one of the warmest of Florence, with an average daytime summer LST values of about 45 °C.

The primary agri-food market in the Florentine municipality was located in this area (about 250,000 m^2). The area shows the most thermal critical urban characteristics: low albedo surfaces (around 0.20), high imperviousness (>80% of the whole area), low tree and grassland (<15%), and no water body surfaces. In addition, one of the main thermal stress indicators outdoor, the Universal Thermal Climate Index (UTCI), revealed a sub-daily period with very strong heat stress (UTCI >40 °C) especially during the central part of the day from 9 a.m. to 4 p.m [4].

The agri-food market plays an important role in the commercial activities of the municipality. From the Local Climate Zones (LCZ) map

Fig. 1. The study area.

of Florence, available on the WUDAPT platform [32], the study area is recognized as LCZ 8 class “Large low-rise” characterized by: open arrangements of large low-rise buildings, few or no trees, land cover mostly paved, steel, concrete, and construction materials.

2.2. Study framework and methodological approach

The methodology was based on the microclimate monitoring and simulation by urban characterization, involving open spatial GIS data from different data sources by using two software tools: a QGIS application [33], coupled with UMEP (Urban Multi-scale Environmental Predictor) plugin [34], and the ENVI-met software [28]. High spatial resolution of analyses and simulations (between 1 m and 5 m) was adopted with the aim to perform microclimate area description at the local scale. Particular attention was placed on the assessment of thermal comfort for workers and the thermal variation effects at different heights by comparing indicators of the thermal environment (air temperature, mean radiant temperature, surface temperature) and UTCI (Universal Thermal Climate Index) [35]. The results were obtained from microclimate modeling simulations of different design scenarios involving different tree patterns in order to verify the thermal variation and discuss the improvement strategies for outdoor thermal comfort.

The study framework (Fig. 2) was based on the following analyses.

1. Analyses of the urban morphology and shading: LIDAR (Laser Imaging Detection and Ranging) data was used in order to obtain the Digital Elevation Model (DEM), the Digital Surface Model (DSM) and the Canopy Digital Surface Model (CDSM) of the study area. The Urban Multi-scale Environmental Predictor (UMEP) plugin was used by combining Python and the QGIS software. Output layers (raster data) at 1 m spatial resolution were obtained.
2. Analysis of urban elements and microclimatic monitoring: data on land cover, surface material, building height, tree height, tree

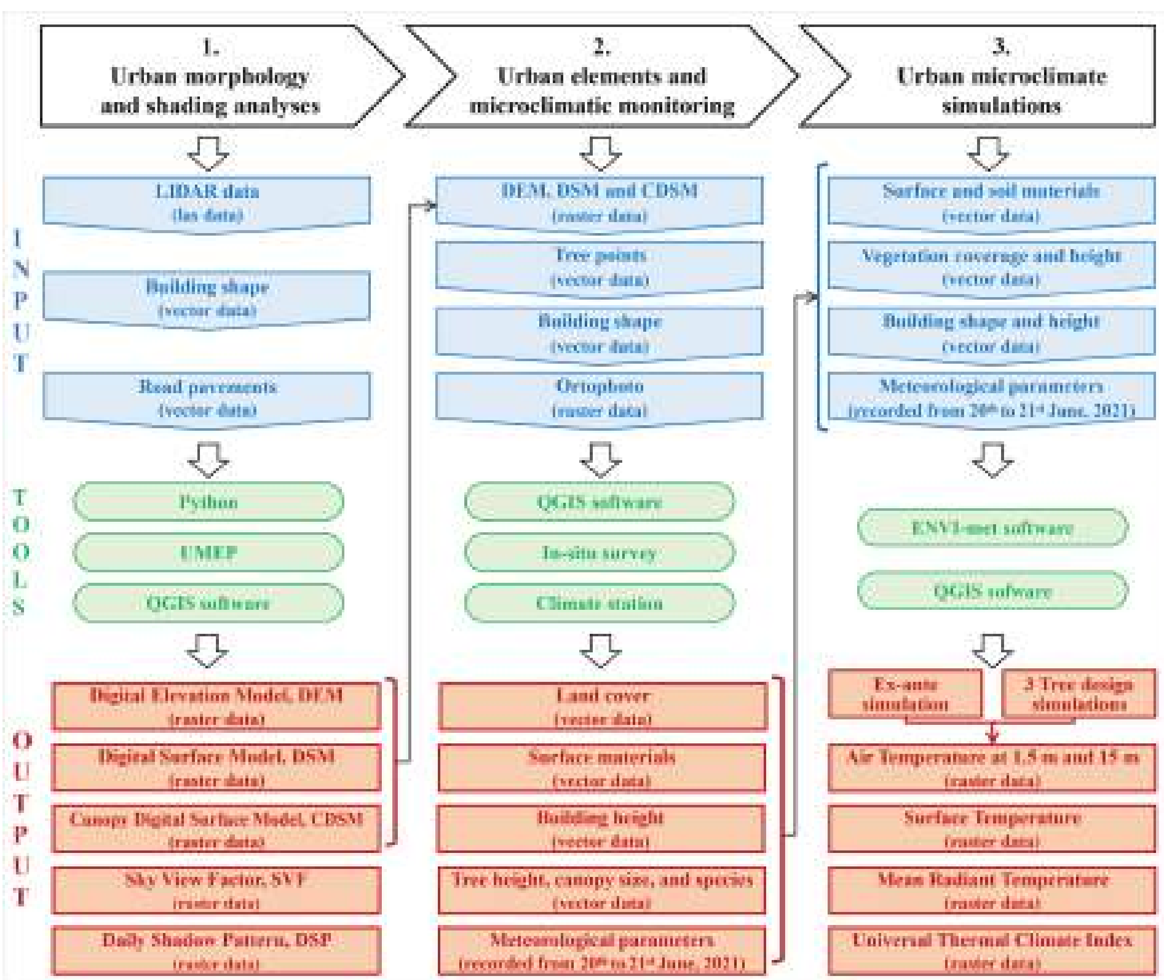

Fig. 2. The study framework. Note: UMEP is the Urban Multi-scale Environmental Predictor tool used within the QGIS and Python environment.

canopy size, and species were collected in order to characterize the study area and the urban elements potentially affecting the outdoor environment microclimate. Urban data (vector data) were collected by QGIS in order to obtain input data necessary for the following simulations performed by ENVI-met software. In addition, the microclimatic monitoring of the study area was conducted through in-situ measurements (during the period from 20 to June 22, 2021) to collect input data for simulations.

3. Urban microclimate simulations: were focused on environmental simulations by considering the current microclimate condition and investigating three tree mitigation scenarios. The ex-ante scenario (A scenario) and the three tree design scenarios (T_5, T_{10} and $T_{5\text{-}10}$ considering trees with a height of 5 m, 10 m and alternating the two heights, respectively) were performed by collecting spatial data in QGIS and ENVI-met simulation. Several output layers at 5 m spatial resolution were retrieved for each scenario, considering environmental indicators of the thermal environment (air temperature, mean radiant temperature, surface temperature), the Urban Thermal Climate Index (UTCI), and indicators on morphology (Sky View Factor) and solar access (shadow hours).

In this study, open data from the GEOscopio platform of the Tuscany Region (source: http://www502.regione.toscana.it/geoscopio/cartoteca.html) and the Open Data Portal of the Florence Municipality (source: http://opendata.comune.fi.it/) were used.

2.3. Urban morphology and shading analyses

The first spatial analyses were conducted in order to describe the morphology and shading of the study area by using LIDAR data. The latter were collected during the year 2017 by the Information System Department of the Florence municipality and were provided in LAS (LASer) format, including height data of the single-point geometry of the surface. The original LIDAR data recorded the height of every single point on the surface and contained one single LAS classification code (as 0 = created, never classified). The FUSION plugin was applied on the latter through a specific code within QGIS, in order to detect the ground points and classify LIDAR data into two classes (ground and no ground). The classified LIDAR data was manipulated within the UMEP plugin by using the Python procedure developed by the Urban Climate Group of the University of Göthenburg (Sweden) [36,37]. The code was further adapted to LIDAR data (the classified LAS layer), using building geometry (vector data), and applying a specific threshold (>1 m) to filter out the vegetation canopy layer. Subsequently, three models (raster data) were retrieved at 1 m spatial resolution, including information on the height of terrain (DTM), surface (DSM), and vegetation canopy (CDSM). In addition, two urban layers (raster data) describing the urban morphology and the summer daily shading patterns were obtained from the DSM and CDSM at 1 m spatial resolution by using the UMEP plugin.

- The Sky View Factor (SVF) describes the urban morphology and returned, with values between 0 and 1, the degree of exposure of a surface to the celestial vault or portion of sky visible from a given point located at ground level [38]. SVF is useful to characterize the radiation properties: the higher its value, the greater the incidence of direct solar radiation [39]. Four categories of urban space can be detected by SVF values [40]: dense space (SVF <0.25); semi-dense space (0.25 < SVF <0.50); semi-open space (0.50 < SVF <0.75); and open space (SVF >0.75).
- The Daily Shadow Pattern (DSP) is the shadow fraction ranging between 0 and 1, where 1 corresponds to the maximum sunlight throughout the day [41] and the position of the sun is calculated using PySolar (http://pysolar.org/). The summer daily shadow pattern of 21st June was selected (from 6:00 to 20:00 local time) in order to perform coherent analyses in the same period of the meteorological monitoring.

2.4. The urban model characterization

The aims of the analyses were to describe the spatial and microclimate characteristics of the study area and to retrieve the necessary input data for the microclimate modeling simulations. Urban data based on meteorological monitoring and the spatial detection of urban elements (buildings, trees, and surfaces) were collected.

2.4.1. Urban spatial characterization

The urban spatial characterization involved the detection of geometry, surface materials, and height of buildings and trees. The geometries of urban elements were provided from the regional topographic database on a scale of 1:2000, available from the GEOscopio Regional Platform previously cited. Data collected from the previous analyses (2.3. Urban morphology and shading analyses) were used to retrieve essential information of the model, i.e. height data of buildings and trees from the DSM and CDSM, respectively.

The material detection was performed on surfaces (roads and pavements) and buildings through an on-site survey, while elevation data of buildings and trees were retrieved by using Zonal Statistics Tool in QGIS software [33] from digital models (DSM and CDSM). In addition, open data from the 2017 Florence Municipality Portal and the 2019 Ortophoto data of the Regional GEOscopio Portal (data source previously cited) were used to retrieve tree species and canopy cover, respectively.

2.4.2. Microclimatic monitoring

Microclimatic monitoring was carried out by positioning sensors in the center of the study area on a building roof at 6 m height. The microclimate monitoring involved the use of a globe-thermometer (DELTA OHM HD 32.1), a thermo hygrometer (Humidity/Temperature Datalogger EXTECH RHT10) and an anemometer (Anemometer Datalogger DT-187). These devices allow the measurement of the main microclimate parameters [31] necessary to evaluate the outdoor thermal environment experienced by the worker according to the international standard regulation (EN ISO 7726).

Hourly globe thermometer temperature, air temperature (AT), relative humidity (RH), wind speed (WS) and wind direction (WD) were recorded by the microclimate station from 20 to June 22, 2021, with the aim to describe microclimatic conditions when the solar altitude is at its maximum levels, i.e. close to the summer solstice in the study area. The monitoring height of measurements of all parameters was about 1.50 m (7.50 m, considering the ground level) and the sample rate was 30 min.

2.5. ENVI-met models

The microclimate modeling simulations were based on the following steps.

- Model set-up and initialization: this section included the model settings, boundary and initial conditions. Information on the simulation data, time settings and the meteorological boundary conditions were also provided.
- Microclimate simulation design and processing: this part provided information on the design settings and output of the simulations carried out on the ex-ante condition and the design scenarios based on three different tree patterns.

In this study, the ENVI-met software was selected to perform microclimate simulations in order to assess the thermal variation from the ex-ante and different tree design scenarios. ENVI-met is an environment modeling software widely used in the research field [26–30] to model different urban characteristics within a specific area and to perform a microclimate simulation. Through this software, different spatial data information of the outdoor model environment (such as data on land cover, urban morphology, tree cover characterization), as well as the meteorological conditions can be managed. The ENVI-met simulations were performed by combining spatial data of the urban characterization of the model and the meteorological monitoring parameters. The ultimate outputs are biometeorological spatial data, providing spatial and temporal variations of the modeling area (such as air temperature, radiative temperature, wind speed and direction, thermal comfort indices, etc.).

2.5.1. Model set-up and initialization

In this study, the model was centered on the main industrial area of Florence. The model digitizing was based on the setting related to the following elements: surface and soil materials, building height, vegetation cover, and tree height and species. Data from the spatial characterization of urban elements (buildings, roads, and trees) and the microclimatic monitoring, related to the previous section (2.4 The urban model characterization), were used in the Envi-met software. In particular, the Geodata to ENVI-met plugin in QGIS was used to convert GIS data (vector data of surfaces, buildings, vegetation cover, and trees including height data) to ENVI-met model area input files. Through this plugin, each model cell was modeled using the GIS vector data related to soil and surface materials, vegetation cover, building height and trees.

The model domain size (X, Y, Z) was set to 600 m × 600 m x 36 m, with 120 × 120 x 12 three-dimensional cells, and the size grid was selected to 5 m × 5 m x 3 m in order to simulate the microclimate of the entire study area at the urban scale. The highest point building was 12 m and the height of 3D model top was 36 m in order to provide sufficient space between building top and model border. However, the real area extent considered in simulations (X and Y dimensions) was 500 m × 500 m, because the most peripheral 50 m for each side of the former study area was potentially affected by boundary bias during simulation.

The ENVI-met runs were carried out for 48 h starting from 20th June, and 21st June was selected as the target day in order to avoid possible simulation errors 24 h before.

Regarding the settings of the meteorological boundary conditions, the Full Forcing method was used, instead of the Simple Forcing method (recommended only when information about air temperature and humidity are present), since it represented the highest precision. In particular, the Full Forcing allowed a forcing of the main meteorological parameters, including air temperature, humidity, wind speed and direction. In this study, the Full Forcing method was applied by using the microclimatic parameters recorded during the days of 20 and June 21, 2021.

Considering the radiation settings, the Indexed View Sphere (IVS) module was enabled in order to enhance the accuracy of radiative heat transfer calculations, in particular of reflected shortwave and longwave radiation fluxes by taking into account multiple interactions between surfaces, buildings and vegetation.

A summary of the main input parameters of the model area was collected by Table 1.

Table 1
Summary of the input parameters of the model.

Parameter	Parameter specification	Study setting
Location	Name of location	Florence, Tuscany Region, Italy
	Latitude	43° 48′ N
	Longitude	11° 13′ E
Simulation date	Start date (YYYY MM DD)	2021 06 20
Simulation time	Start time (HH:MM)	00:00
	Total simulation time (h)	48
Meteorology	Meteorological boundary conditions	Full forcing method
Radiation	Raytracing precision	Finer resolution
	Indexed View Sphere (IVS) module	IVS module enabled

2.5.2. Microclimate simulation design and processing

Four modelling simulations were conducted in this study: the ex-ante simulation (Scenario A), based on the current spatial characteristics, and three tree design simulations were performed in order to provide information on the new simulated thermal situation, compared with the ex-ante condition.

A preliminary analysis involved a comparison between the simulated air temperature obtained by the ex-ante simulation and the observed measurements collected by the microclimate monitoring, in this way providing a support for the validity of the ENVI-met model. The coefficient of determination (R^2) and the root mean square error (RMSE) were chosen to verify the accuracy of the ENVI-met model.

Subsequently, particular attention was paid to design proper mitigation scenarios for the future: involving new dominant tree species (deciduous) and preserving the current urban function simultaneously, in addition to the available areas for truck handling (loading/unloading goods). The design simulations involved three design scenarios including 133 trees positioned in rows considering distances of 10 m between one plant and another, accounting for different tree patterns.

1) Scenario T_5: trees with 5 m height;
2) Scenario T_{10}: trees with 10 m height;
3) Scenario $T_{5\text{-}10}$: alternating trees with heights of 5 m and 10 m.

The tree distance of 10 m in rows was selected considering the space needed to allow the typical working activities (i.e. handling, transport, loading and unloading of material) and movement of the working vehicles, such as for example trucks that were usually parked in front of the buildings of the simulated area.

Regarding the selection of trees with heights of 5 m and 10 m, medium-sized trees were selected in the model with the aim of reaching a compromise between the needs of thermal comfort and the management of working space. In addition, medium-sized trees were selected paying particular attention to maintain the size of the current trees and, especially, considering the growth potentially achieved by the design trees over a period of 3–5 years.

The rows of trees were designed on the middle line of roads for functional reasons related to working activities specific of the agri-food area and to consider only the shading effect provided by trees, thus avoiding any interaction with the contribution due to the shading by buildings. Output data of microclimatic indicators were analyzed considering the daytime period at 9:00 and 15:00 on 21st June. The following environmental indicators describing the meteorological and surface thermal conditions were obtained: Air Temperature (AT), Mean Radiant Temperature (MRT), Surface Temperature (ST). In addition, the Universal Thermal Climate Index (UTCI) [35], was obtained from the ENVI-met outputs in order to quantify the thermal stress levels of each scenario. UTCI, the state-of-the-art of outdoor rational biometeorological indices, is considered as an equivalent temperature (°C) based on the most recent scientific progress in human thermo-physiology, biophysics, and the heat exchange theory [42]. The UTCI model was applied internationally in several application areas, including occupational thermal stress [43]. The UTCI is based on advanced human thermoregulation and air-temperature-related clothing models and is able to predict the impact of outdoor climate referred to a male person of 35 years, about 1.70 m height, 73 kg weight, generating a total metabolic rate of about 135 W/m^2 that corresponds to a moderate activity according to the international regulation (UNI EN ISO 8996:2004).

Thus, thermal stress in this study was calculated for workers performing moderate labor activity represented by the following tasks: sustained work with hands and arms, with arms and legs (driving off-road trucks, tractors or work machinery); work with arms and trunk (work with jackhammer, tractor assembly, plastering, intermittent handling of moderately heavy material, weeding, hoeing, picking fruit or vegetables); push or pull light wagons or wheelbarrows; walk at speeds between 3.5 and 5.5 km/h. These work activities fall well within those performed by most of the workers employed in the industrial area under study, therefore above all operations of handling, transport, loading and unloading of materials from trucks, trailers, and storage shelves, driving of vehicles not conditioned for moving of material, alternating exposures outdoors (directly exposed to the sun) or in shaded areas (under covers or non-air-conditioned sheds).

UTCI is categorized by ten thermal heat and cold stress classes in terms of equivalent temperature [42].

- Extreme heat stress: UTCI >46 °C;
- Very strong heat stress: 38 °C < UTCI <46 °C;
- Strong heat stress, 32 °C < UTCI <38 °C;
- Moderate heat stress: 26 °C < UTC <32 °C;
- No thermal stress: 9 °C < UTCI <26 °C;
- Slightly cold stress: 0 °C < UTCI <9 °C;
- Moderate cold stress: −13 °C < UTCI <0 °C;
- Very strong cold stress: −27 °C < UTCI < −40 °C;
- Extreme cold stress: UTCI < - 40 °C.

Hourly AT, MRT and UTCI were analyzed at the pedestrian height of 1.5 m, while the first parameter was further investigated at a medium modeling height of 15 m.

The averaged values of the previously mentioned parameters were calculated considering two daytime periods (morning and afternoon) on the road surfaces, as the most affected by tree design scenarios. A non-parametric statistical test, the Wilcoxon signed-rank test [44], was used to investigate the significance of the null difference hypothesis (H0) within the selected parameters between no intervention and mitigation scenarios.

Additional ENVI-met outputs regarding urban morphology and solar access were considered for the target day (21st June) in order to compare potential differences on the design areas: averaged values of SVF and shadow hours were retrieved for each scenario. All ENVI-met outputs were transformed into raster data and manipulated in the QGIS (QGIS Development Team, 2023) and R software (using the package "exactextract") [45] by retrieving averaged values recorded on the road surfaces.

3. Results

3.1. Urban microclimate characterization

The area analyzed in this study was 250,000 m^2 size, where the most represented surface was road pavements (about 55%), mainly covered by asphalt, followed by building areas (40%) and green areas (5%). Additional information about the urban characteristics related to land cover, height of buildings and trees, tree species, Sky View Factor and Daily Shadow Pattern were included in Fig. 3.

Table 2 summaries the dimensional and morphological characteristics related to the three main urban elements of the study area (buildings, pavements and green areas).

The average height of buildings was 8 m (ranging from 3 m to 12 m)

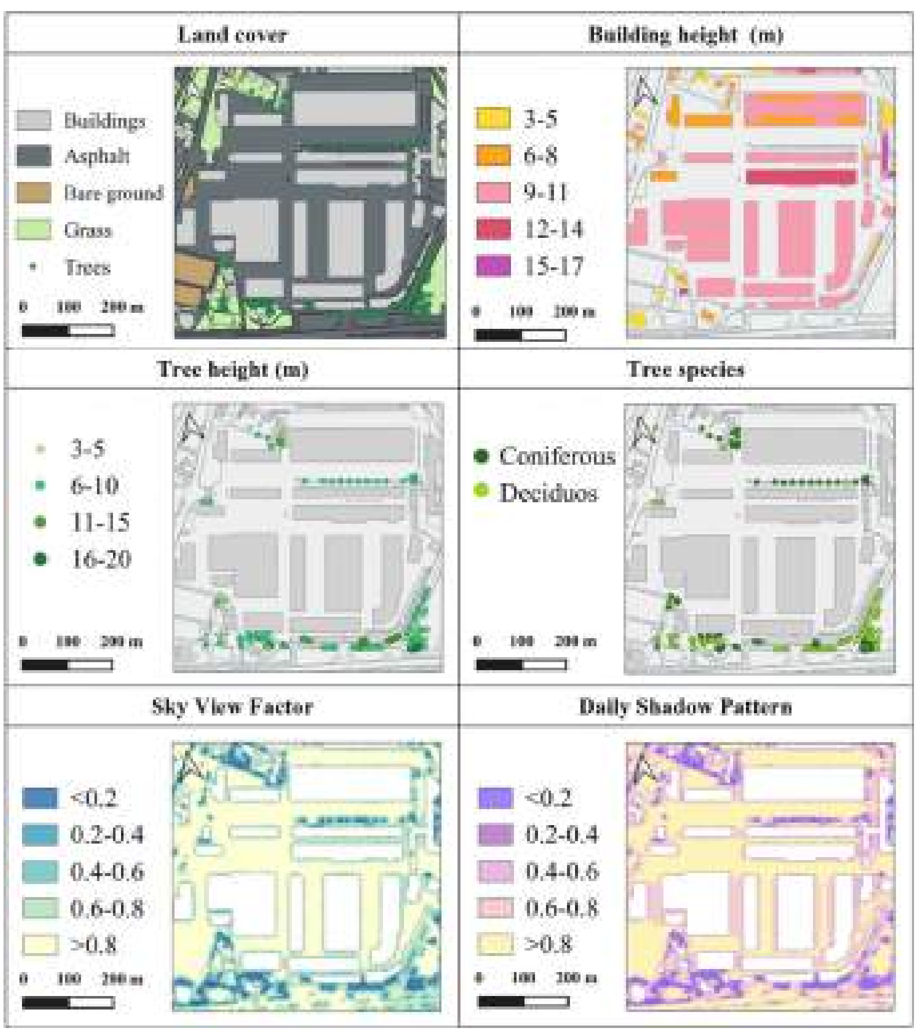

Fig. 3. Urban characteristics of the study area obtained from geospatial and LIDAR data.

Table 2
Coverage area and morphology characteristics of urban surfaces.

Urban characteristics	Buildings	Pavements	Green areas
Area [mq]	100,300	137,275	12,425
Area [%]	40.1	54.9	5.0
SVF (mean) [adim.]	–	0.77	0.52
DSP (mean) [adim.]	–	0.70	0.56

Notes: SVF: Sky View Factor; DSP: Daily Shadow Pattern.

and the road width ranged between 35 m and 60 m. A number of 112 trees were recorded (49 in street canyons, and 63 in green areas) with an average coverage of less than 5%. In addition, the most common tree species were deciduous (such as *Celtis Australis, Tilia Europaea, and Ulmus*) with an average height of 10 m and a canopy of 10 m in diameter. The average meteorological parameters recorded from 20 to June 21, 2021 on the study area were shown in Table 3.

3.2. Indicators of the thermal environment of the tree design scenarios

A preliminary support to the validity of the ENVI-met model was provided by the verification of the air temperature simulated by the ex-ante model compared with the air temperature collected by the micro-climate monitoring for the selected day (21st June 2021). This analysis revealed a good model reliability showing an R^2 value of 0.940 and RMSE of 1.25 °C (Fig. S1), in agreement with previous studies [46,47].

The modeling maps of the ex-ante (A) and the tree design scenarios (T_5, $T_{5\text{-}10}$, T_{10}) about soil and surface materials, vegetation cover, and three-dimensional models are shown in Fig. 4. The maps showed the input data necessary to define and develop the model area (in the SPACES component of the ENVI-met software) to be used for the simulations.

The microclimate output maps of the ex-ante (A) and tree design scenarios (T_5, $T_{5\text{-}10}$, T_{10}) were shown in Fig. 5.

Averaged morning and afternoon variations of the environmental indicators of the thermal environment were investigated for the selected urban domain (road surfaces) where different tree patterns were planned (Table 4).

From Wilcoxon signed-rank test, the averaged values of the investigated parameters revealed in the three tree design scenarios were all significantly different ($p < 0.001$) from the ex-ante situation. The parameter that showed the least variability was AT, showing a maximum difference of 0.4 °C in the T_{10} scenario compared to the ex-ante situation. On the other hand, greater variations were observed considering the MRT and above all at the surface level. In particular, the highest MRT (6.0 °C in the afternoon and 5.6 °C in the morning periods), ST (4.1 °C and 3.0 °C) and UTCI (1.7 °C and 1.5 °C) variations compared to the ex-ante situation were observed in T_{10} scenario. Less marked variations were observed in the $T_{5\text{-}10}$ scenario while the lowest ones concerned the T_5 scenario during both daytime periods. All scenarios revealed "very strong heat stress" conditions (UTCI ranging between 39.9 °C and 41.5 °C) during afternoon, whereas transition from "strong heat stress" (33.1 °C–32.3 °C) in A, T_5 and $T_{5\text{-}10}$ scenarios to "moderate heat stress levels" (31.6 °C) in T_{10} scenario were observed during the morning period.

Table 3
Meteorological parameters of the microclimatic monitoring analysis of the study area.

Meteorological parameters (at 7.5 m height above ground)	
Average air temperature (min-max) [°C]	29.0 (19.7–33.5)
Average globe temperature (min-max) [°C]	37.7 (25.9–48.9)
Average relative humidity (min-max) [%]	50.9 (39.9–80.0)
Average wind speed (min-max) [m/s]	2.0 (1.6–2.5)
Wind direction (0: N, 90: E, 180: S, 270: W) (mode value) [°]	180 (S)
Roughness length [m]	0.01

The 133 trees planned to be planted on street canyons during the three simulations represented about 6%, 9%, and 13% of the road coverage, respectively in the T_5, $T_{5\text{-}10}$, T_{10} design scenarios (Table 5). The highest Tree Canopy Coverage (TCC) on road surfaces (about 13%) were in T_{10} scenario, where the new TCC (trees with 10 m of height and canopy diameter) represented about 10% of the road surfaces. Considering the urban morphology and solar access, the highest SVF decrease (about 23%) and SH increase (2.5 h) were observed in T_{10}, followed by $T_{5\text{-}10}$ scenario (16% and 1.5 h) and T_5 (6% and 0.3 h).

4. Discussion

Since the early 2000s, the need for climate-sensitive urban design is significantly increasing [11] and many countries decided to implement national and local strategies for climate change adaptation and mitigation, including NBS, GBI, high-reflective materials for pavements, roads, and roofs.

According to several research centers, rapid and sustained mitigation and accelerated implementation of adaptation actions in this decade would reduce projected losses and damages for humans and ecosystems, and deliver many co-benefits, especially for air quality and health [1]. Urban planners and designers need to develop city models to accommodate increasing population pressures reducing the impact on the urban environment and climate change, with particular attention to industrial areas considered priority zones for heat mitigation strategies. Numerous studies discussed heat-mitigating design solutions related to urban form [48], such as building arrangement and street orientation, urban vegetation [49], cool materials [50], and water-based cooling systems [51].

The predominance of impervious cover and the absence or scarcity of vegetation determine critical thermal environments in urban areas: direct solar radiation increases pavement surface temperatures, effecting the local microclimate. This aspect is more pronounced in industrial and commercial areas, mainly covered by artificial surfaces and characterized by the scarcity of tree cover, in this way unable to reduce the surface temperature through the shading effect and evapotranspiration.

Urban landscaping and the development of tree cover spaces (tree species, height and canopy cover) play a key role in UHI mitigation, influencing the variations of temperature in cities [52,53]. Currently, research on heat mitigation scenarios based on tree patterns was conducted at various scales [25,54–57] and several studies demonstrated that trees provide better cooling effects on high-temperature asphalt surfaces [25,27,58]. In particular, trees provide direct shading on pavements, which also decrease pavements maintenance costs by reducing the rate of pavement deterioration [13]. Recent studies have shown that trees cooling capacity depends on different physical or structural characteristics of trees and their location of placement in an urban environment [55]. However, the costs associated with the maintenance of the greenery should also be considered, which in any case are significantly lower than the benefits obtained from the plants [59].

Moreover, it was widely recognized that the transmission of light through the canopy cover plays an important role in effecting the surface temperature [60] and the increases in the percentage of vegetative cover reduces solar absorption during summer [61].

Several studies conducted in urban areas worldwide observed a reduction between 5 °C and 25 °C in pavement temperature under the tree shading compared to the non-shaded areas [13]. In addition, the larger the tree canopy is the more effective the shading result [27,62]: trees with larger crowns favor a decrease of the SVF below the tree, in this way reducing the amount of solar radiation received and allowing the cooling effect. A previous study [15] showed that trees were more effective in low urban density (high SVF) than in compact urban areas (low SVF). The modeling study revealed that air temperature reduction (1.5 °C reduction) is the most profound for the high SVF scenario.

The assessment of urban morphology and solar radiation access, for instance by considering SVF and SH, in the design area is extremely

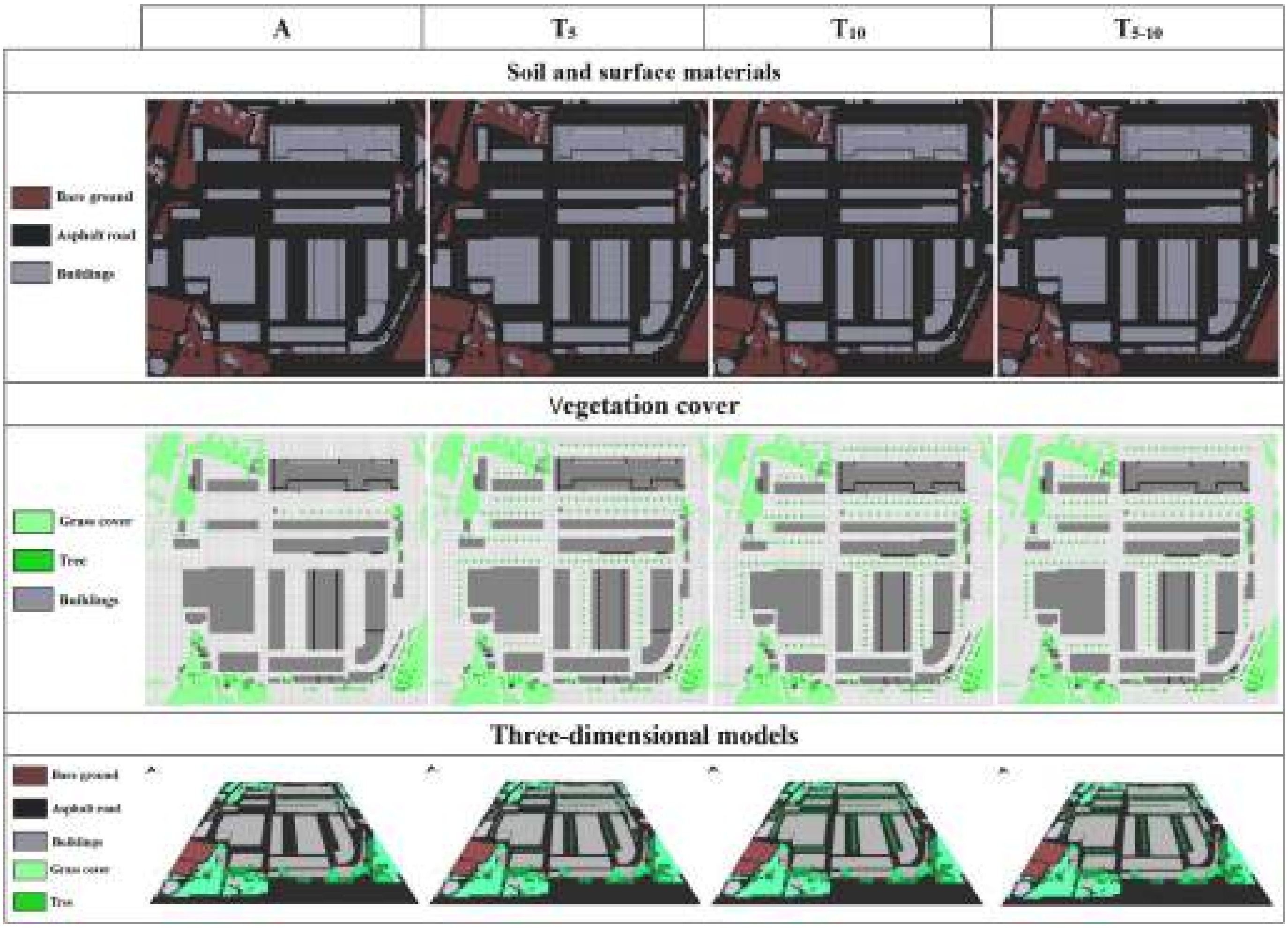

Fig. 4. Input data used within the ENVI-met software to define the model area of the ex-ante scenario (A), tree design scenarios of 5 m (T_5), 10 m (T_{10}), and alternating 5 m and 10 m ($T_{5\text{-}10}$). Focus on soil and surface materials, vegetation cover, and three-dimensional models.

important in order to consider the shading conditions of the buildings on both sides of the street [13], better describing the relation between cooling and shading effects provided by trees and further urban elements (such as buildings).

Our study provides an important contribution regarding the impact of street-level greenery on environmental and surface temperatures, taking into account human height and morphological factors like SVF and SH. Spatial data on urban morphology and solar exposure was essential to detect the most solar-exposed areas where to simulate targeted design scenarios aimed at improving the thermal environment of the industrial area. The best-planned tree scenario in terms of reduction in UTCI and thermal parameters involved trees with a height and a canopy diameter of 10 m (T_{10}). In this scenario, the design tree pattern (133 trees representing a 10% increase on the road surface cover) was characterized by the highest decrease in MRT, ST and UTCI, respectively during both afternoon and morning periods, and the highest decrease of SVF and increase of SH. The highest thermal decreases were observed in the afternoon (at 3:00 p.m.) for almost every scenario and this result is in accordance with previous studies [27,63], showing that the best cooling effect occurs between 1:00 p.m. and 3:00 p.m.

In particular, our microclimate simulations showed that trees play a crucial role in cooling the road surfaces, in accordance with recent simulation results [27]: trees with a height of 10 m showed the best cooling effect favoring significant decreases of 6 °C in MRT and 4 °C in ST compared with the ex-ante situation.

In accordance with previous studies [64,65], trees had minimal effect on air temperature, but showed a significant effect on lowering surface temperature and mean radiant temperature thereby improving the thermal comfort. It was widely demonstrated that mean radiant temperature is mostly affected by surfaces' albedo and by the shading from both buildings and trees because of its dependence on radiative fluxes (especially direct shortwave radiation) [28].

As expected, surface and mean radiant temperatures played an important role on the tree mitigation scenarios, instead of air temperature. Low airflow values (values under 2 m/s^2) were measured within the study area during the entire day, and, little daytime variations in wind speed (below 0.5 m/s^2) were simulated between the ex-ante and the tree design scenarios under the new tree canopies at 1.5 m height. These results were in agreement with a previous study [65] that confirmed that light wind (under 2 m/s^2) can limit its potential effect on the local heat exchange processes.

The urban characteristics linked to tree shading changed moving from A to T_{10} scenario, determining potentially better shading features: a 23% decrease in SVF (with SVF = 0.59, corresponding to "semi-open space" category) and about 2.5 h increase in SH were observed in T_{10} when compared with A.

The best thermal improvement in the agri-food market will be potentially achieved by the tree design scenario considering trees of 10 m height, whereas lower cooling effect will be obtained by the scenario involving trees of 5 m height. Our findings revealed the importance of tree height and canopy cover dimension to provide significant variations of urban microclimate in a complex urban area such as industrial and

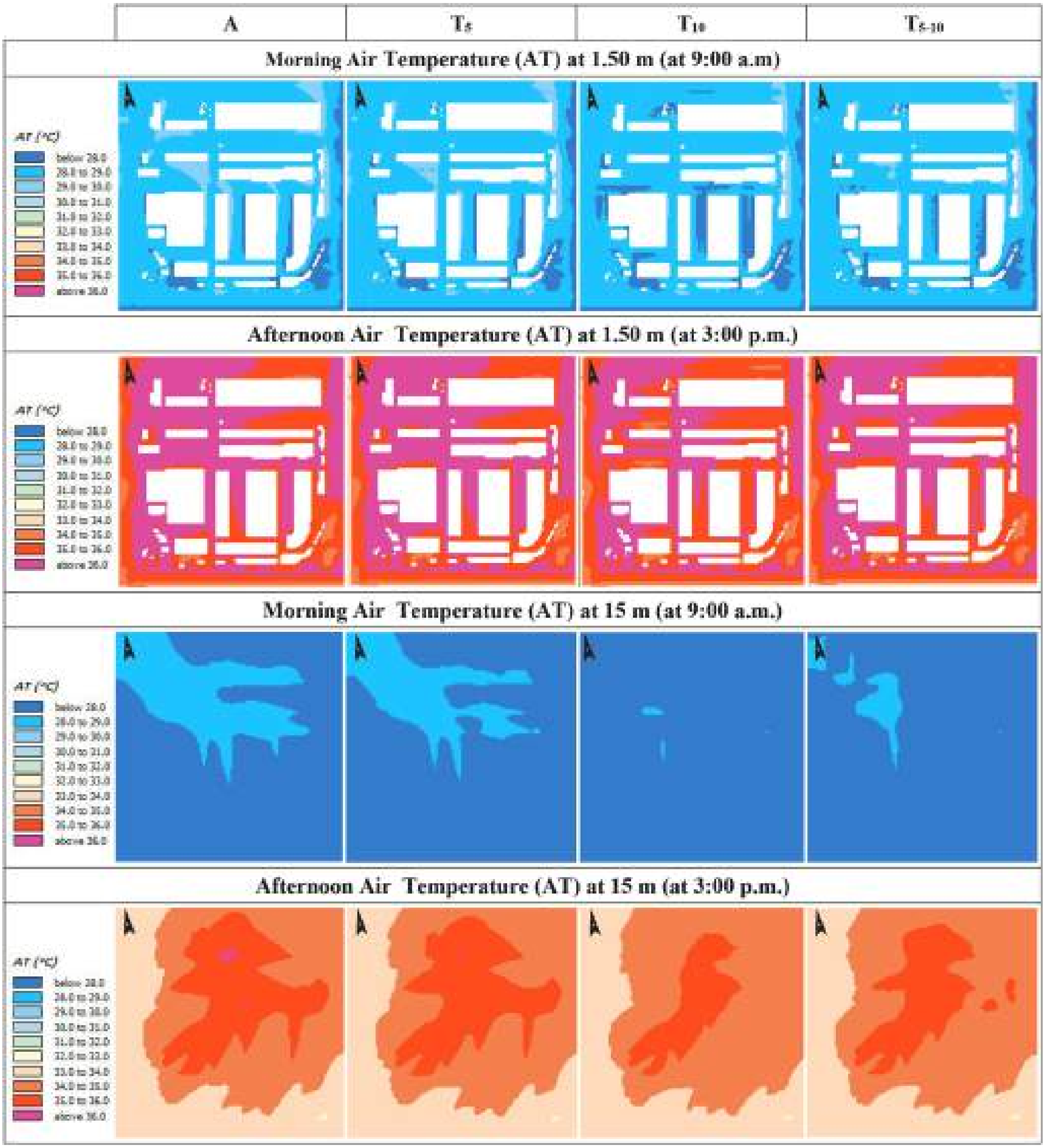

Fig. 5. Microclimate simulation in the morning (at 9:00 a.m.) and afternoon periods (at 3:00 p.m.) from ex-ante scenario (A), tree design scenarios of 5 m (T_5), 10 m (T_{10}), and alternating 5 m and 10 m ($T_{5\text{-}10}$). Focus on Air Temperature (AT) at the height of 1.5 m and 15 m, Surface Temperature (ST), Mean Radiant Temperature (MRT) and Universal Thermal Climate Index (UTCI) at the height of 1.5 m.

commercial zones. For this reason, it should be considered that, in urban complex contexts, a significant cooling effect could be reached several years after planting (depending on tree species), therefore upon reaching a height of about 10 m. Our results suggest that, with the aim of achieving the best result, it is worth planning new trees in target areas with proper characteristics (tree density, height, canopy cover size), therefore selecting proper trees with large canopies and rapid growth. A virtuous tree example at fast growth is the Paulownia Tomentosa, a deciduous tree (Paulowniaceae family), being able to grow from small cracks in pavements and walls. This specific tree is widely cultivated as an ornamental tree in parks and gardens [66] and was highlighted as a good solution to reach the selected goal in urban and specifically

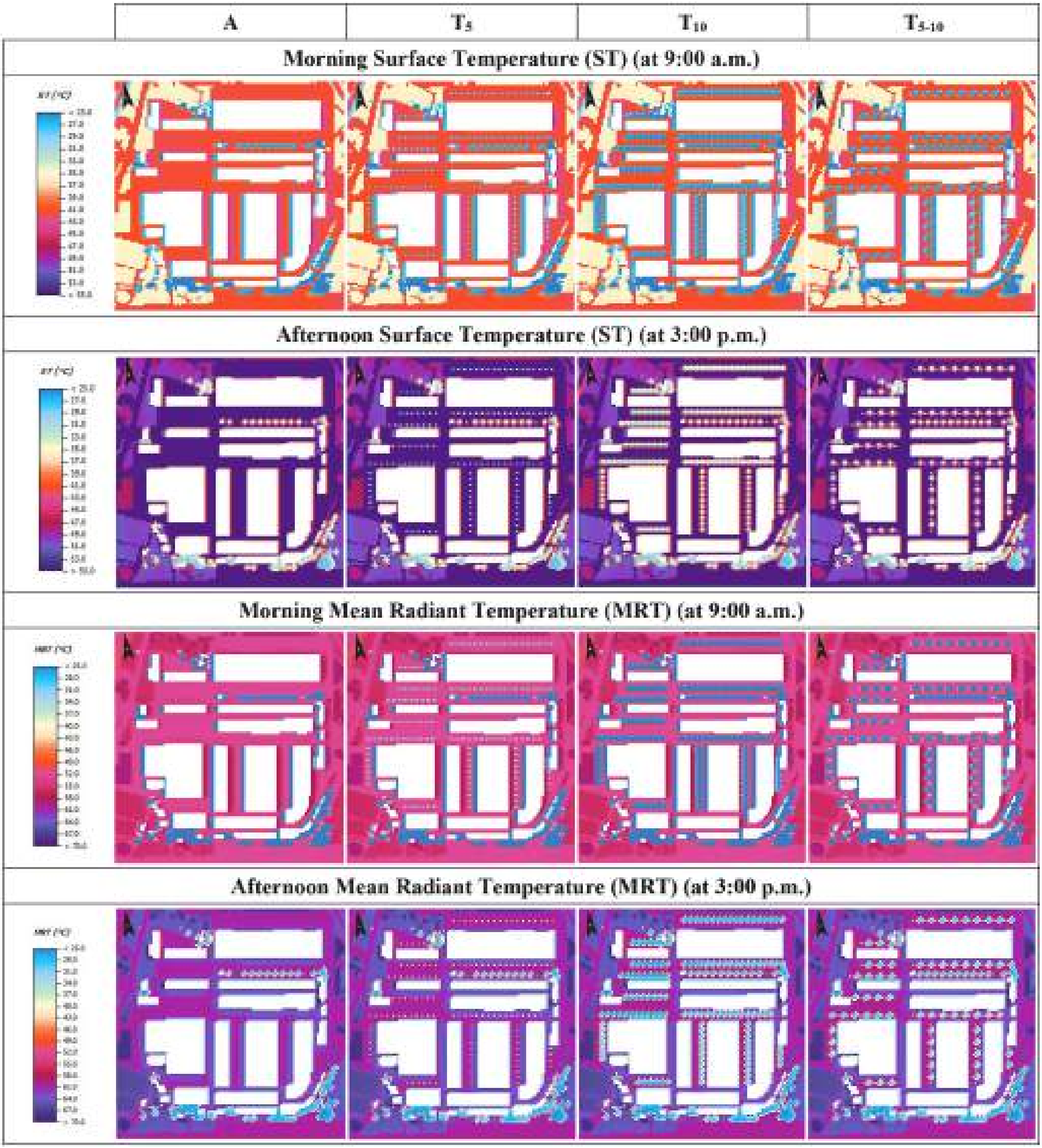

Fig. 5. (*continued*).

industrial areas [67].

Despite tree benefits in industrial areas were widely demonstrated, specially referred to thermal comfort, air temperature regulation, emissions, and air pollution reduction [65,68,69], this study addressed particular attention also concerning the design intervention selection, in terms of tree location and dimensions.

This study selected specific parameters in order to conduct microclimate simulations in the industrial area of Florence with particular attention to tree patterns, according to a sustainable pattern for both thermal comfort needs and the conduct of work activities. Appropriate tree distances, tree height, and crown size were selected properly in order to allow the regular performance of the work activities, as well as for the work vehicles' movement. In this study, the selection of tree rows in the middle of the road with a distance of 10 m between trees and a maximum height of 10 m was designed with particular attention to allowing adequate road space for the work activities and producing

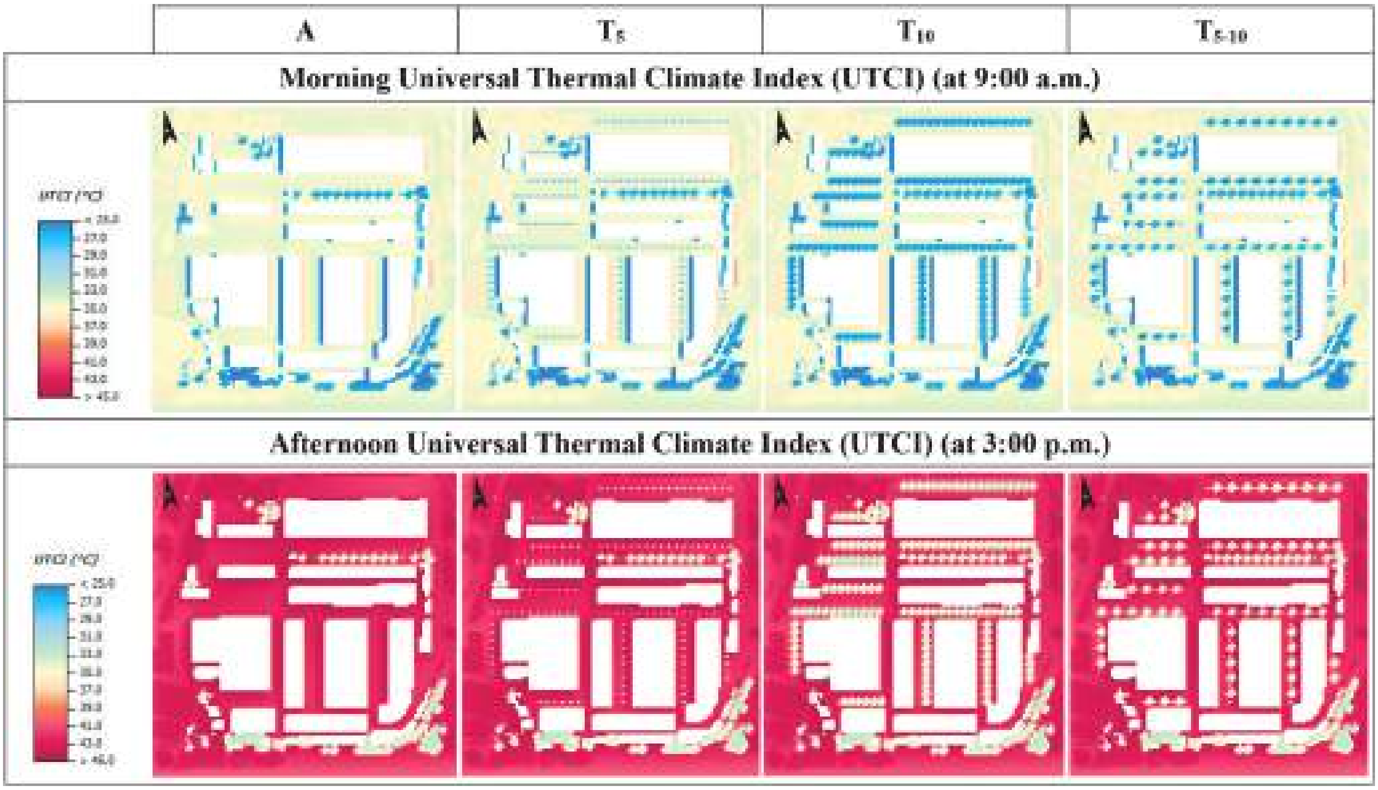

Fig. 5. (*continued*).

Table 4
Averaged values of the indicators of the thermal environment in the selected periods (at 9:00 a.m. and 3:00 p.m.) recorded on the overall road surfaces from the A, T_5, T_{10}, and $T_{5\text{-}10}$ scenarios.

Analyses on the overall road surfaces								
Indicators of thermal environment	Morning period (9:00 a.m.)				Afternoon period (3:00 p.m.)			
	A	Differences from the current ex-ante situation (A)			A	Differences from the current ex-ante situation (A)		
		T_5	$T_{5\text{-}10}$	T_{10}		T_5	$T_{5\text{-}10}$	T_{10}
AT at 1.5 m (mean ± sd) [°C]	28.6 ± 0.4	−0.0	−0.1	−0.2	36.4 ± 0.6	−0.1	−0.2	−0.4
AT at 15 m (mean ± sd) [°C]	27.9 ± 0.4	−0.0	−0.1	−0.2	34.9 ± 0.8	−0.0	−0.1	−0.2
ST (mean ± sd) [°C]	38.5 ± 6.2	−0.6	−1.8	−3.0	52.5 ± 7.9	−0.6	−2.3	−4.1
MRT at 1.5 m (mean ± sd) [°C]	47.9 ± 12.4	−1.0	−3.3	−5.6	57.2 ± 11.8	−0.8	−3.4	−6.0
UTCI at 1.5 m (mean ± sd) [°C]	33.1 ± 3.3	−0.2	−0.8	−1.5	41.5 ± 3.1	−0.2	−0.9	−1.7

Note: AT: Air Temperature; ST: Surface Temperature; MRT: Mean Radiant Temperature; UTCI: Urban Thermal Climate Index; sd: standard deviation.

Table 5
Tree number and Tree Canopy Coverage (TCC) on road surfaces, and averaged Sky View Factor (SVF) and Shadow Hour (SH) values.

Road surfaces				
	A	T_5	$T_{5\text{-}10}$	T_{10}
Tree (n.)	49	182	182	182
TCC (mq)	4600	7925	12,875	17,900
TCC (%)	3.4	5.8	9.4	13.1
SVF mean (adim.)	0.77	0.72	0.65	0.59
SH mean	4.6	4.9	6.1	7.1

Note: TCC: Tree Canopy Coverage; SVF: Sky View Factor; SH: Shadow Hours. TCC% values are referred to road coverage.

processes, especially for vehicle operations.

Moreover, this study referred to an industrial area that has characteristics corresponding to the “Large low-rise” Local Climate Zone (LCZ) classification, therefore characterized by open arrangements of large low-rise buildings, few or no trees, land cover mostly paved, steel, concrete, and construction materials. It is possible to classify and identify this class of urban typology through the WUDAPT platform also for other Italian and international cities [32]. The findings of this study can certainly provide a contribution for those urban areas that have similar characteristics in terms of distribution of large low-rise buildings, vegetation types and imperviousness cover. In addition, the work also can certainly be extended to those industrial contexts that envisage work activities similar to those considered in this study, where it is not possible to intervene by distorting the paved area which must maintain productive characteristics.

The originality and scientific contribution of this study lay in the performance of detailed urban model characterization within the selected industrial area, mainly from open geospatial data and meteorological monitoring, followed by urban microclimate simulations based on realistic tree design approaches for mitigating thermal conditions.

The scientific contribution also lays in the area selection within an industrial fabric, mainly characterized by typical industrial elements that potentially determined surface thermal anomalies (such as large low-rise buildings, impermeable surfaces and scarce vegetation cover) and that made interesting the comparison with mitigation interventions in other industrial context at the same latitude.

Furthermore, the microclimate simulations were characterized by realistic methodology approaches, in particular regarding the detailed analyses conducted for the model characterization (including urban features and meteorological parameters) and the tree design mitigation scenarios.

The realistic approach of this study was mainly based on three tree design scenarios, depending on different tree heights, considering the tree location in the most solar exposed areas, with particular attention at preserving the work space.

4.1. Study limitation

The microclimate model output of this study showed some limitations linked to the ENVI-met modeling. Despite ENVI-met has a solid physical foundation, simulation still cannot fully represent the real world because of the use of "approximations" [31,70]. For this reason, further studies will perform in-situ measurements in order to validate results from design scenario simulations and to avoid possible misjudgment. Additional limitations were included in the simulation as the anthropogenic heat generated by humans, vehicles, and mechanical cool systems is not accounted for in the model [55,56,71], as the ENVI-met software has not been implemented for these aspects [64]. Recent studies on microclimate modeling [64,65,72,73] confirmed the ENVI-met software limitation in not considering the heat anthropogenic heat emissions and the need to carry out further effort and improvements in this direction. In addition, further important tree parameters might be parameterized, such as LAI (Leaf Area Index), LAD (Leaf Area Density), and further indicators of landscape metrics related to green cover [17] that are important indicators for urban surface temperatures and tree cooling [56]. In our study, an average default LAD value (equal to 1) was used.

Despite this study was not focused on the airflow patterns, important meteorological parameters like the wind speed were considered in the ENVI-met simulations, but not included in the results because of little daytime variations in wind speed (under 0.5 m/s^2) between scenarios under the new tree canopies at 1.5 m height. Another limit concerns the use of the UTCI for occupational purposes. In our study, only the simulation of heat stress associated with moderate physical activity has been considered, while the implementation of other situations related to occupational thermal stress (i.e. the modification of metabolic rate, clothing levels and exposure duration) should be considered for future developments [42].

In addition, future analyses should also consider the effect of cool materials on pavements and roofs, in this way considering also other potential thermal mitigation solutions to be integrated with the use of NBS with the aim to improve the thermal environment.

5. Conclusion

Mitigating the surface thermal hot-spots in industrial areas during daytime hours represents a pressing challenge that requires immediate attention from the scientific and academic communities. Our findings revealed that increasing the number of trees and thus improving the canopy cover significantly enhances the cooling effect depending on tree characteristics.

In particular, a 10% increase in the tree canopy on road surfaces revealed a significant impact on thermal environments, showing the greatest effect at the surface level on both daytime periods analyzed. The greatest cooling impact was observed during the afternoon (3 p.m.) considering the tree design scenario covering overall about 13% of road surfaces and represented by trees with 10-m height and the largest canopy cover (T_{10}): MRT, ST and UTCI decreased by 6.0 °C, 4.1 °C and 1.7 °C respectively when compare to the ex-ante situation. The lowest cooling effect (but still statistically significant) was observed considering a mitigating three design scenario by using trees with 5 m height (T_5), leading to a 0.6 °C and 1 °C decrease in ST and MRT, respectively compared to the ex-ante situation.

Based on our simulations, it is concluded that thermal mitigation strategies based on trees should be focused on criteria accounting for specific tree characteristics, with particular regard to selecting trees with fast growth able to reach the most effective height to mitigate thermal effects (10 m height and with a canopy cover of almost 10 m diameter).

The results of this study indicated that trees are important elements for urban mitigation strategies and that tree shading on urban surfaces can strongly contribute to mitigating surface thermal hot-spot areas and improve the thermal comfort for outdoor workers. However, urban planners and policy makers should be aware of the different impacts these strategies have and their application must be analyzed according to the local climatic, morphological, and urban functional contexts.

CRediT authorship contribution statement

Giulia Guerri: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Alfonso Crisci:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Data curation, Conceptualization. **Marco Morabito:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All outputs of the study (spatial layers and codes) are available on the Zenodo platform (https://doi.org/10.5281/zenodo.8388599).

Acknowledgments

We are particularly grateful to the Urban Climate research group of the University of Gothenburg (Sweden), who provided the code useful to extract spatial digital surface and elevation models from LIDAR data, by using Python coupled with the UMEP plugin. The authors acknowledge the research group of the Institute of BioEconomy of the National Research Council of Bologna (Italy) for providing the scientific knowledge and support for the ENVI-met simulations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110854.

References

[1] IPCC, Summary for Policymakers, In: climate change 2023: synthesis report. A report of the intergovernmental panel on climate change, in: H. Lee, J. Romero (Eds.), Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, IPCC, Geneva, Switzerland, 2023, p. 36.

[2] M. Munafò, Consumo di Suolo, Dinamiche Territoriali e Servizi Ecosistemici, vol. 15, Report ISPRA, 2020. ISBN 978-88-448-1013-9, https://www.snpambiente.it/2020/07/22/consumo-di-suolo-dinamiche-territoriali-eservizi-ecosistemici-edizione-2020/. (Accessed 30 May 2023).

[3] C.I. Portela, K.G. Massi, T. Rodrigues, E. Alcântara, Impact of urban and industrial features on land surface temperature: evidences from satellite thermal indices, Sustain. Cities Soc. 56 (2020), https://doi.org/10.1016/j.scs.2020.102100.

[4] G. Guerri, A. Crisci, L. Congedo, M. Munafò, M. Morabito, A functional seasonal thermal hot-spot classification: focus on industrial sites, Sci. Total Environ. 806 (2021), 151383, https://doi.org/10.1016/j.scitotenv.2021.151383.

[5] M. Santamouris, Using cool pavements as a mitigation strategy to fight urban heat island—a review of the actual developments, Renew. Sustain. Energy Rev. 26 (2013) 224–240, https://doi.org/10.1016/j.rser.2013.05.047.
[6] J. Murray, D. Heggie, From urban to national heat island: the effect of anthropogenic heat output on climate change in high population industrial countries, Earth's Future 4 (2013) 298–304, https://doi.org/10.1002/2016EF000352.
[7] T.R. Oke, Boundary Layer Climates, second ed., Wiley and Sons, New York, NY, USA, 1978.
[8] D. Di Blasi, A. Marinaccio, C. Gariazzo, L. Taiano, M. Bonafede, A. Leva, M. Morabito, P. Michelozzi, F.K. de' Donato, On behalf of the worklimate collaborative group. Effects of temperatures and heatwaves on occupational injuries in the agricultural sector in Italy, Int. J. Environ. Res. Publ. Health 20 (2023) 2781, https://doi.org/10.3390/ijerph20042781.
[9] C. Gariazzo, L. Taiano, M. Bonafede, A. Leva, M. Morabito, F. de' Donato, A. Marinaccio, Association between extreme temperature exposure and occupational injuries among construction workers in Italy: an analysis of risk factors, Environ. Int. 171 (2023), 107677, https://doi.org/10.1016/j.envint.2022.107677.
[10] International Labour Organization, Working on a Warmer Planet: the Impact of Heat Stress on Labour Productivity and Decent Work, International Labour Office, Geneva, ILO, 2019.
[11] P. Kumar, A. Sharma, Study on importance, procedure, and scope of outdoor thermal comfort–A review, Sustain. Cities Soc. 61 (2020), 102297, https://doi.org/10.1016/j.scs.2020.102297.
[12] E. Jamei, P. Rajagopalan, M. Seyedmahmoudian, Y. Jamei, Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort, Renew. Sustain. Energy Rev. 54 (2016) 1002–1017, https://doi.org/10.1016/j.rser.2015.10.104.
[13] V.R.S. Cheela, M. John, W. Biswas, P. Sarker, Combating urban heat island effect—a review of reflective pavements and tree shading strategies, Buildings 11 (2021) 93, https://doi.org/10.3390/buildings11030093.
[14] Z. Tan, K.L. Lau, E. Ng, Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment, Energy Build. 114 (2016) 265–274, https://doi.org/10.1016/j.enbuild.2015.06.031.
[15] H.M. Imran, J. Kala, A.W.M. Ng, Effectiveness of vegetated patches as Green Infrastructure in mitigating Urban Heat Island effects during a heatwave event in the city of Melbourne, Weather Clim. Extrem. 25 (2019), 100217, https://doi.org/10.1016/j.wace.2019.100217.
[16] X.D. Xiao, L. Dong, H. Yan, The influence of the spatial characteristics of urban green space on the urban heat island effect in Suzhou Industrial Park, Sustain. Cities Soc. 40 (2018) 428–439, https://doi.org/10.1016/j.scs.2018.04.002.
[17] K. McGarigal, Landscape pattern metrics, in: A.H. El-Shaarawi, W.W. Piegorsch (Eds.), Encyclopedia of Environmetrics, second ed. vol. 6, Wiley, Chichester, UK, 2012. ISBN 978-0-470-05733-9.
[18] A. Aboelata, S. Sodoud, Evaluating the effect of trees on UHI mitigation and reduction of energy usage in different built up areas in Cairo. Build, Environ. Times 168 (2020), 106490, https://doi.org/10.1016/j.buildenv.2019.106490.
[19] Y. Lan, Q. Zhan, How do urban buildings impact summer air temperature? The effects of building configurations in space and time, Build. Environ. 125 (2017) 88–98, https://doi.org/10.1016/j.buildenv.2017.08.046.
[20] I. Lima, V. Scalco, R. Lamberts, Estimating the impact of urban densification on high-rise office building cooling loads in a hot and humid climate, Energy Build. 182 (2019) 30–44, https://doi.org/10.1016/j.enbuild.2018.10.019.
[21] Y. Chen, B. Zheng, Y. Hu, Numerical simulation of local climate zone cooling achieved through modification of trees, albedo and green roofs—a case study of changsha, China, Sustainability 12 (2020) 2752, https://doi.org/10.3390/su12072752.
[22] P.E. Vásquez-Álvarez, C. Flores-Vázquez, J.C. Cobos-Torres, S.L. Cobos-Mora, Urban heat island mitigation through planned simulation, Sustainability 14 (2022) 8612, https://doi.org/10.3390/su14148612.
[23] G. Battista, E. de Lieto Vollaro, L. Evangelisti, R. de Lieto Vollaro, Urban overheating mitigation strategies opportunities: a case study of a square in Rome (Italy), Sustainability 14 (2022), 16939, https://doi.org/10.3390/su142416939.
[24] R. Cocci Grifoni, G. Caprari, G.E. Marchesani, Combinative study of urban heat island in ascoli piceno city with remote sensing and CFD simulation—climate change and urban health resilience—CCUHRE project, Sustainability 14 (2022) 688, https://doi.org/10.3390/su14020688.
[25] C.C. Pezzuto, N.L. Alchapar, E.N. Correa, Urban cooling technologies potential in high and low buildings densities, Solar Energy Advances 2 (2022), 100022, https://doi.org/10.1016/j.seja.2022.100022.
[26] E. Fiorillo, L. Brilli, F. Carotenuto, L. Cremonini, B. Gioli, T. Giordano, M. Nardino, Diurnal outdoor thermal comfort mapping through envi-met simulations, remotely sensed and in situ measurements, Atmosphere 14 (2023) 641, https://doi.org/10.3390/atmos14040641.
[27] S. Yan, T. Zhang, Y. Wu, C. Lv, F. Qi, Y. Chen, X. Wu, Y. Shen, Cooling effect of trees with different attributes and layouts on the surface heat island of urban street canyons in summer, Atmosphere 14 (2023) 857, https://doi.org/10.3390/atmos14050857.
[28] M. Bruse, H. Fleer, Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model, Environ. Model. Software 13 (1998), https://doi.org/10.1016/S1364-8152(98)00042-5.
[29] S. Tsoka, A. Tsikaloudaki, T. Theodosiou, Analyzing the ENVI-met microclimate model's performance an assessing cool materials and vegetation applications – a review, Sustain. Cities Soc. 43 (2018) 55–76, https://doi.org/10.1016/j.scs.2018.08.009.
[30] Y. Yang, E. Gatto, Z. Gao, R. Buccolieri, T.E. Morakinyo, H. Lan, The "plant evaluation model" for the assessment of the impact of vegetation on outdoor microclimate in the urban environment, Build. Environ. 159 (2019), 106151, https://doi.org/10.1016/j.buildenv.2019.05.029.
[31] Z. Liu, W. Cheng, C.Y. Jim, T. Morakinyo, Y. Shi, E. Ng, Heat mitigation benefits of urban green and blue infrastructures: a systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4, Build. Environ. 200 (2021), 107939, https://doi.org/10.1016/j.buildenv.2021.107939.
[32] M. Demuzere, J. Kittner, B. Bechtel, LCZ Generator: a web application to create Local Climate Zone maps, Front. Environ. Sci. 9 (2021), 637455, https://doi.org/10.3389/fenvs.2021.637455.
[33] QGIS Development Team, QGIS geographic information system. Open source geospatial foundation project, 2023. Available online: http://qgis.osgeo.org.
[34] F. Lindberg, C.S.B. Grimmond, A. Gabey, B. Huang, C.W. Kent, T. Sun, N. Theeuwes, L. Järvi, H. Ward, I. Capel- Timms, Y.Y. Chang, P. Jonsson, N. Krav, D. Liu, D. Meyer, F. Olofson, J.G. Tan, D. Wästberg, L. Xue, Z. Zhang, Urban Multi-scale Environmental Predictor (UMEP) - an integrated tool for city-based climate services, Environ. Model. Software 99 (2018) 70–87, https://doi.org/10.1016/j.envsoft.2017.09.020.
[35] G. Jendritzky, R. de Dear, G. Havenith, UTCI—why another thermal index? Int. J. Biometeorol. 56 (2012) 421–428, https://doi.org/10.1007/s00484-011-0513-7.
[36] F. Lindberg, C. Grimmond, Nature of vegetation and building morphology characteristics across a city: influence on shadow patterns and mean radiant temperatures in London, Urban Ecosyst. 14 (2011) 617–634, https://doi.org/10.1007/s11252-011-0184-5.
[37] M. Hedblom, F. Lindberg, E. Vogel, J. Wissman, K. Ahrné, Estimating urban lawn cover in space and time: case studies in three Swedish cities, Urban Ecosyst. 20 (2017) 1109–1119, https://doi.org/10.1007/s11252-017-0658-1.
[38] F. Lindberg, C.S.B. Grimmond, Continuous sky view factor maps from high resolution urban digital elevation models, Clim. Res. 42 (2010) 177–183, https://doi.org/10.3354/cr00882.
[39] M.K. Svenson, Sky view factor analysis—implications for urban air temperature differences, Meteorol. Appl. 11 (2004) 201–211, https://doi.org/10.1017/S1350482704001288.
[40] G. Baghaeipoor, N. Nashrollani, The effect of sky view factor on air temperature in high-rise urban residential environments, J. Daylighting 6 (2019) 42–51, https://doi.org/10.15627/jd.2019.6.
[41] F. Lindberg, C.S.B. Grimmond, The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: model development and evaluation, Theor. Appl. Climatol. 105 (2011) 311–323, https://doi.org/10.1007/s00704-010-0382-8.
[42] P. Bröde, D. Fiala, B. Lemke, T. Kjellstrom T, Estimated work ability in warm outdoor environments depends on the chosen heat stress assessment metric, Int. J. Biometeorol. 62 (2018) 331–345, https://doi.org/10.1007/s00484-017-1346-9.
[43] C. Di Napoli, A. Messeri, M. Novák, J. Rio, J. Wieczorek, M. Morabito, S. Pedro, A. Crisci, F. Pappenberger, The Universal Thermal Climate Index as an Operational Forecasting Tool of Human Biometeorological Conditions in Europe, 2021. https://doir.org/10.1007/978-3-030-76716-7_10.
[44] F. Wilcoxon, Individual comparisons by ranking methods, Biometrics Bull. 1 (1945) 80–83, https://doi.org/10.2307/3001968.
[45] R. R Core Team, A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2023. https://www.R-project.org/.
[46] X. He, W. Gao, R. Wang, Impact of urban morphology on the microclimate around elementary schools: a case study from Japan, Build. Environ. 206 (2021), 108383, https://doi.org/10.1016/j.buildenv.2021.108383.
[47] W. Ouyang, T. Sinsel, H. Simon, T.E. Morakinyo, H. Liu, E. Ng, Evaluating the thermal-radiative performance of ENVI-met model for green infrastructure typologies: experience from a subtropical climate, Build. Environ. 207 (2022), 108427, https://doi.org/10.1016/j.buildenv.2021.108427.
[48] M. Taleghani, L. Kleerekoper, M. Tenpierik, A. Van Den Dobbelsteen, Outdoor thermal comfort within five different urban forms in The Netherlands, Build, Environ. Times 83 (2015) 65–78, https://doi.org/10.1016/j.buildenv.2014.03.014.
[49] J. Gaspari, K. Fabbri, M. Lucchi, The use of outdoor microclimate analysis to support decision making process: case study of Bufalini square in Cesena, Sustain. Cities Soc. 42 (2018) 206–215, https://doi.org/10.1016/j.scs.2018.07.015.
[50] M. Santamouris, A. Synnefa, T. Karlessi, Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions, Sol. Energy 85 (2011) 3085–3102, https://doi.org/10.1016/j.solener.2010.12.023.
[51] J. Kim, J. Kang, Evaluating the efficiency of fog cooling for climate change adaptation in vulnerable groups: a case study of Daegu Metropolitan City, Build. Environ. 217 (2022), 109120, https://doi.org/10.1016/j.buildenv.2022.109120.
[52] C.S. Greene, J.K. Peter, Beyond fractional coverage: a multilevel approach to analyzing the impact of urban tree canopy structure on surface urban heat islands, Appl. Geogr. 95 (2018) 45–53, https://doi.org/10.1016/j.apgeog.2018.04.004.
[53] F. Aram, E.H. García, E. Solgi, S. Mansournia, Urban green space cooling effect in cities, Heliyon 5 (2019), https://doi.org/10.1016/j.heliyon.2019.e01339, 1-31.
[54] M. Morabito, A. Crisci, G. Guerri, A. Messeri, L. Congedo, M. Munafò, Surface urban heat islands in Italian metropolitan cities: tree cover and impervious surface influences, Sci. Total Environ. 751 (2021), 142334, https://doi.org/10.1016/j.scitotenv.2020.142334.
[55] T.E. Morakinyo, L. Kong, K.K.-L. Lau, C. Yuan, E. Ng, A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort, Build. Environ. 115 (2017) 1, https://doi.org/10.1016/j.buildenv.2017.01.005.

[56] T.E. Morakinyo, K.K.-L. Lau, C. Ren, E. Ng, W. Ouyang, Right tree, right place (urban canyon): tree species selection approach for optimum urban heat mitigation - development and evaluation, Sci. Total Environ. 719 (2020), https://doi.org/10.1016/j.scitotenv.2020.137461.
[57] M. Jiao, W. Zhou, Z. Zheng, J. Yan, J. Wang, Optimizing the shade potential of trees by accounting for landscape context, Sustain. Cities Soc. 70 (2021), 102905, https://doi.org/10.1016/j.scs.2021.102905.
[58] M. Sharmin, M.G. Tjoelker, S. Pfautsch, M. Esperon-Rodriguez, P.D. Rymer, S. A. Power, Tree crown traits and planting context contribute to reducing urban heat, Urban For. Urban Green. 83 (2023), 127913, https://doi.org/10.1016/j.ufug.2023.127913.
[59] C. Choi, P. Berry, A. Smith, The climate benefits, co-benefits, and trade-offs of green infrastructure: a systematic literature review, J. Environ. Manag. (2021), 112583, https://doi.org/10.1016/j.jenvman.2021.112583.
[60] A. Rafiee, D. Eduardo, K. Eric, Local impact of tree volume on nocturnal urban heat island: a case study in Amsterdam, Urban For. Urban Green. 16 (2016) 50–61, https://doi.org/10.1016/j.ufug.2016.01.008.
[61] H.M. Imran, J. Kala, A.W.M. Ng, S. Muthukumaran, Effectiveness of vegetated patches as Green Infrastructure in mitigating Urban Heat Island effects during a heatwave event in the city of Melbourne, Weather Clim. Extrem. 25 (2019) 1–14, https://doi.org/10.1016/j.wace.2019.100217.
[62] C. Wang, Z.H. Wang, Y.H. Ryu, A single-layer urban canopy model with transmissive radiation exchange between trees and street canyons, Build. Environ. 191 (2021), 107593, https://doi.org/10.1016/j.buildenv.2021.107593.
[63] V.S. Duval, G.M. Benedetti, K. Baudis, The impact of street trees on the urban microclimate, Bahía Blanca, Argentina. Investig. Geogr. 73 (2020) 171–188, https://doi.org/10.14198/INGEO2020.DBB.
[64] T.E. Morakinyo, Y.F. Lam, Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort, Build. Environ. 103 (2016) 262–275, https://doi.org/10.1016/j.buildenv.2016.04.025.
[65] F.M. Alves, A. Gonçalves, M.R. del Caz-Enjuto, The use of envi-met for the assessment of nature-based solutions' potential benefits in industrial parks—a case study of argales industrial park (valladolid, Spain), Infrastructure 7 (2022) 85, https://doi.org/10.3390/infrastructures7060085.
[66] R. Owfi, Ecophysiological study of Paulownia tomentosa, International Journal of Current Research 9 (2017) 63582–63591.
[67] M.U. Kukadia, Kiri (Paulownia tomentosaSteud.): a miracle tree, Indian J. For. 19 (1996) 194–195.
[68] D.R. Richards, T.K. Fung, R.N. Belcher, P.J. Edwards, Differential air temperature cooling performance of urban vegetation types in the tropics, Urban For. Urban Green. 50 (2020), 126651, https://doi.org/10.1016/j.ufug.2020.126651.
[69] T. Yasinta, M. Karuniasa, A. Sodry, Availability and needs of urban forest vegetation in industrial areas: analyzing Landsat 8 Imagery using the normalized difference vegetation index method, IOP Conf. Ser. Earth Environ. Sci. 716 (2021), 012137, https://doi.org/10.1088/1755-1315/716/1/012137.
[70] Y. Yang, D. Zhou, Y. Wang, D. Ma, W. Chen, D. Xu, Z. Zhu, Economical and outdoor thermal comfort analysis of greening in multistory residential areas in Xi'an, Sustain. Cities Soc. 51 (2019), 10173, https://doi.org/10.1016/j.scs.2019.101730.
[71] U. Berardi, The outdoor microclimate benefits and energy saving resulting from green roofs retrofits, Energy Build. 121 (2016) 217–229, https://doi.org/10.1016/j.enbuild.2016.03.021.
[72] M. Santamouris, Cooling the cities—a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments, Sol. Energy 103 (2014) 682–703, https://doi.org/10.1016/j.solener.2012.07.003.
[73] L. Bande, A. Afshari, D. Al Masri, M. Jha, L. Norford, A. Tsoupos, P. Marpu, Y. Pasha, P. Armstrong, Validation of UWG and ENVI-met models in an abu dhabi district, based on site measurements, Sustainability 11 (2019) 4378, https://doi.org/10.3390/su11164378.