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Differing potential of nature-based solutions for heat mitigation across European urban areas

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ABSTRACT

Urban areas are increasingly affected by severe heat waves due to climate change, threatening people's health, and posing enormous challenges to human society. Nature-based solutions (NbS) are an effective way to mitigate heat, but the influence of urban green spaces (UGS) characteristics remains insufficiently understood. This study aims to evaluate the UGS potential across European urban areas by (1) quantifying UGS characteristics (percentage, size, canopy cover) and population proximity to UGS, (2) assessing the relative influence of UGS characteristics on urban heat mitigation under 27 scenarios and across four biogeographical regions by simulating cooling effects in a virtual setting, and (3) identifying groups of urban areas with differing potential of enhancing UGS for improving heat mitigation. Our results reveal spatial heterogeneity of UGS characteristics (median percentage 10.3%, median size 10,657 m^2, median canopy cover 9.4%) and contrasting patterns of population proximity to UGS across Europe, emphasizing the need to expand UGS and to address environmental justice issues. Simulations show that increasing UGS percentage from 6.2% to 17.2% and enlarging canopy cover within UGS from 1.7% to 44.6% in the virtual city significantly reduced the average city-wide temperature, ranging from -0.44 °C in the Mediterranean region to -0.16 °C in the Boreal region. Our findings suggest that people living in southern and eastern European urban areas, where UGS are scarcer, will mostly benefit from an expansion of UGS and more even UGS distribution, thereby improving accessibility. In northern regions, there is potential to increase cooling effects by increasing canopy cover. However, these findings require validation against empirical temperature data before being applied to specific urban areas.

Introduction

Climate change massively alters environmental conditions with huge impacts on ecosystems and people. One major issue associated with rising temperatures is the increase in the frequency and intensity of heat waves, affecting a growing share of the global population [1]. Heat waves lead to increased mortality, as temperatures above the optimal range are associated with higher death rates [2–4], especially of people belonging to vulnerable groups such as elderly and chronically ill people [3,5,6]. Moreover, urbanization processes lead to a higher number of people being affected by heat waves, as people living in urban areas are particularly exposed to heat and heat waves due to the urban heat island (UHI) effect [7,8]. The UHI is a meteorological phenomenon resulting from an artificialization of the surface, i.e., sealing of formerly vegetated surfaces [9,10], leading to increased air temperatures, for example, between 0.57 and 2.54 C across 100 European cities [11]. In addition, anthropogenic heat sources, originating, for example, from transportation, heating, cooling, lighting, and people's metabolism contribute to higher temperatures [12]. Under future climate conditions, the impacts on human health from heat stress are expected to aggravate, as heat wave frequency and intensity is predicted to increase in the future [13–16]. Recent model simulations predict that heat wave days in European urban areas occur on average between 6.5 days per year at the 0.5 C global warming level and 33.3 days at 2.0 C by 2100, which is sixfold in Mediterranean regions and around fourfold in northern countries [15].

Mitigation measures in urban areas are urgently needed to mitigate adverse effects of climate change on people's health [2,3,17,14]. There are various strategies to limit heat gain and enable the release of stored heat, for example, by using different building materials, modifying

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urban spatial design to facilitate ventilation, reducing anthropogenic heat sources, and increasing blue and green spaces [18]. However, the costs and benefits of such strategies need to be carefully evaluated [19], and sometimes, they cannot be implemented in already existing urban areas, as it is impossible to entirely change the urban layout [20]. There is an increasing focus on nature-based solutions (NbS) as a cost-effective strategy to mitigate the impacts of heat and heat waves [21,17,22], providing biodiversity co-benefits and other related societal benefits such spaces for recreation [23,24]. NbS can comprise green infrastructure (i.e., vegetation-based such as parks, gardens, and trees), blue infrastructure (i.e., water-based such as ponds, lakes, rivers), and grey infrastructure (i.e., engineered greening such as green walls, green facades, and roofs), contributing to cooler temperatures, as surfaces covered by vegetation have a higher evapotranspiration compared to sealed surfaces, decreasing the sensible heat flux [9,25]. In this study, we focus on urban green spaces (UGS), which, for example, have been found to reduce the air temperature by approximately 1.1 °C on average [26,27].

The effectiveness of UGS can vary depending on several design characteristics. The amount of shading vegetation is one key characteristic, as tree canopy provides not only shade to people but has also positive effects on the air temperature in the surroundings of UGS [28, 29]. Particularly, complex vegetation structures comprising trees and shrubs of different heights have higher cooling effects than a homogenous vegetation layer without trees [30–32]. In addition, cooling effectiveness increases with surfaces covered by vegetation [33,34] due to reduced heat storage and increased evapotranspiration [9,35]. Similarly, several studies also indicate that larger-sized UGS contribute more to urban cooling than small UGS [36,33,34,37]. Another important characteristic influencing UGS effectiveness is their spatial distribution, which should benefit most of the population. Since cooling effects of UGS decline with increasing distance from UGS [37], the number of UGS and their spatial arrangement within the urban area influence spatial patterns of heat mitigation [38]. Consequently, residents living in areas that are distant from UGS may not have access to the benefits [39–41].

Although there is the need for expanding UGS to address adverse effects of climate change, UGS are being reduced in many places due to the high demand for living and working space, leading to the densification of urban areas [42,43]. Against this trend, the recent EU Nature Restoration Law requires EU Member States to preserve UGS area and tree cover until 2030, and to increase their total area from 2031 onwards (EU regulation 2024/1991). Thus, decision-makers need more information on how UGS should be designed to be most effective in terms of cooling capacity while also ensuring fair distribution of benefits to the residing population [44,45]. However, despite the increasing number of studies focusing on the role of UGS for heat mitigation, comprehensive knowledge on how to design UGS in European cities is still insufficient. Many studies focused on only one or few cities [46,47,34], while other studies, which included a higher number of cities, often addressed specific UGS characteristics. For example, studies assessed almost 300 cities across Europe, focusing on the availability of UGS [48] and evaluating the role of canopy cover on heat mitigation [49]. While Marando et al. [27] simulated the temperature difference between a baseline and a no-vegetation scenario in 601 European cities, insights into specific UGS characteristics and justice issues remain underexplored.

Addressing such knowledge gaps in the design of UGS for mitigating heat waves in European cities, this study aims to evaluate the potential of enhancing UGS across European urban areas, hypothesizing that European urban areas differ in vulnerability to summer heat waves due to varying characteristics of UGS, and that some urban areas are less "prepared" than others to future heat waves. The specific objectives were (1) to characterize UGS of European urban areas in terms of percentage, size, and canopy cover, and the population's spatial distribution in respect to UGS, (2) to assess the relative influence of percentage, size, and canopy cover of UGS on urban heat mitigation under 27 scenarios in a virtual setting, and (3) to identify groups of urban areas and the related potential of enhancing UGS for improving heat mitigation. For this purpose, we combine an analysis of the current real-world situation in terms of UGS characteristics across Europe with the simulation of heat mitigation under scenarios in a virtual city, accounting for climatic variations across distinct biogeographical regions [50]. Using a virtual city instead of the real setting of individual cities allows for controlling the individual UGS characteristics and evaluating their respective influence on cooling effects. Based on the characteristics of UGS in urban areas and the simulation results, we discuss the potential of enhancing UGS in European urban areas to support the future design of UGS, accounting for issues related to environmental efficiency and justice.

Materials and methods

Preparing the database

Copernicus urban atlas 2018

For the analysis of UGS characteristics across European urban areas and the definition of scenarios, we used the Copernicus Urban Atlas 2018 (https://land.copernicus.eu/local/urban-atlas). It provides spatial land cover data for 788 functional urban areas with >50,000 inhabitants in the 38 countries that are either members or cooperating countries of the European Environment Agency (EEA38) as well as the United Kingdom (Fig. 1). The vector data contains 17 urban classes with a minimum mapping unit of 0.25 ha and integrated population estimates for each land cover type. In addition, a street tree layer is available, including contiguous rows or patches of urban trees that cover at least 500 m^2 and have a minimum width of 10 m. In this study, we focused on UGS located in the core urban area, which is generally delineated according to political boundaries, and which represents the most densely populated areas within functional urban areas (Dijkstra et al. 2019). In most European countries, the core urban area corresponds to the second level of Local Administrative Units (LAU2), commonly referring to municipalities or communes. Thus, after removing the less densely populated commuting zones of the functional urban areas based on the boundaries provided by the Urban Atlas, we obtained 737 core urban areas. Consistent with our focus on characterizing the structural properties of UGS rather than city-wide cooling potential, we quantified percentage and size of UGS, as well as canopy cover within UGS (Table 1) for each urban core area. All data were prepared using ArcGIS Pro 3.2 (ESRI, Redlands, CA, USA).

Designing a virtual city and scenarios

We used a virtual city to assess the relative importance of UGS characteristics on cooling effects. A virtual setting provides a laboratory-like environment under controlled, repeatable conditions [52,53]. In this environment, one UGS characteristic (e.g., percentage) can be adjusted while all other characteristics (i.e., size, canopy cover) remain constant, allowing to isolate the effect of specific UGS characteristics under consistent testing conditions. This ensures that results are comparable across regions, which is nearly impossible in real cities where multiple factors interact simultaneously. Moreover, it allows simulation of hypothetical scenarios, which may not yet exist in real cities, but help planners anticipate outcomes and design effective strategies [52]. Such preliminary technical analyses help identify the most effective options for participatory planning, ensuring stakeholder discussions are grounded in evidence-based strategies that anticipate cooling effects and potential drawbacks before committing resources [54]. By distilling complex European urban diversity into a single virtual city, broad patterns and mechanisms can be identified, enabling generalizable insights and fair comparisons [53]. We designed the virtual city representing average structural characteristics of European urban areas (Fig. 2), enabling a standardized benchmark across Europea, while also accounting for differences in climate, vegetation, and geology across Europe. Real cities can then be compared to this benchmark to assess how they deviate from the European average and to identify gaps,

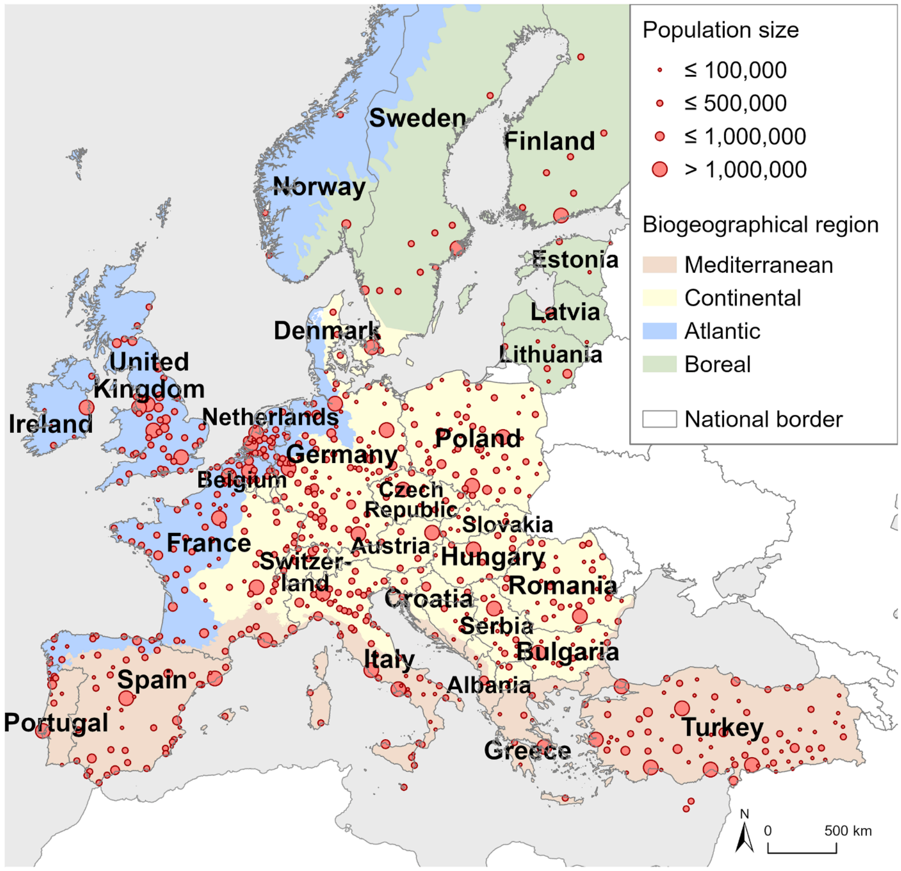

Fig. 1. Location of functional urban areas in European countries included in the Copernicus Urban Atlas 2018 (https://land.copernicus.eu/local/urban-atlas) and distribution of major biogeographical regions [51]. Please note that only larger countries are labeled.

Table 1
Extraction of the characteristics of urban green spaces (UGS) for each urban area based on the Copernicus Urban Atlas 2018 (https://land.copernicus.eu/local/urban-atlas).

UGS characteristic	Description	Unit	Database
Percentage	Percentage of UGS area in relation to the total area of urban fabric	%	- Polygons representing UGS (14,100 - green urban areas) - Polygons representing urban fabric, i.e., 11,100 - continuous urban fabric (S.L. > 80 %), 11,210 - discontinuous dense urban fabric (S.L. 50 - 80 %), 11,220 - discontinuous medium density urban fabric (S.L. 30 – 50 %), 11,230 - discontinuous low density urban fabric (S.L. 10 – 30 %), 11,240 - discontinuous very low-density urban fabric (S.L. < 10 %)
Size	Median UGS size across all UGS	m^2	- Polygons representing UGS (14,100 - green urban areas)
Canopy cover	Median canopy cover within UGS	%	- Polygons representing UGS (14,100 - green urban areas) - Urban tree data overlaid with the UGS polygons to derive the share of canopy cover within each UGS

opportunities, and tailored strategies for heat mitigation.

Based on the urban areas included in the Copernicus Urban Atlas 2018 (https://land.copernicus.eu/local/urban-atlas), we constructed the basic spatial dataset for the virtual city, as well as 27 scenarios representing different arrangements of UGS characteristics. This process involved the following steps:

1) The entire spatial extent of the entire virtual city was determined by summing up the area of all land cover types that represented urban fabric in each urban area (i.e., 11,100 - continuous urban fabric (S.L. > 80 %), 11,210 - discontinuous dense urban fabric (S.L. 50 - 80 %), 11,220 - discontinuous medium density urban fabric (S.L. 30 – 50 %), 11,230 - discontinuous low density urban fabric (S.L. 10 – 30 %), 11,240 - discontinuous very low-density urban fabric (S.L. < 10 %)). We then used the median area of urban fabric across all European urban areas for the virtual city, resulting in an area of 17.49 km^2. This virtual city is comparable in size to several small and medium-sized European cities, such as Constanța (Romania), Funchal (Portugal), Groningen (Netherlands), Luzern (Switzerland), Middlesbrough (United Kingdom), Regensburg (Germany), and Treviso(Italy). For the size of all cities, see Table S1.
2) To account for common gradients in European urban morphology, we separated the urban fabric into two categories according to the proportion of sealed surface layer (S.L.), a measure of imperviousness used in the Urban Atlas. Using a 50 % threshold, we identified (1) a core zone with dense urban fabric (50.6 %, 8.85 km^2), and (2) an outer ring of medium to low density urban fabric (49.4 %, 8.64 km^2). These two classes were implemented as parametric inputs in the virtual city, assigning each grid cell the typical surface properties associated with its class (e.g., crop coefficient, albedo), rather than using explicit GIS-based building footprints or heights.
3) Using the quartile breaks, i.e., Q1 (25th percentile), Q2 (median), and Q3 (75th percentile), of percentage, size, and canopy cover

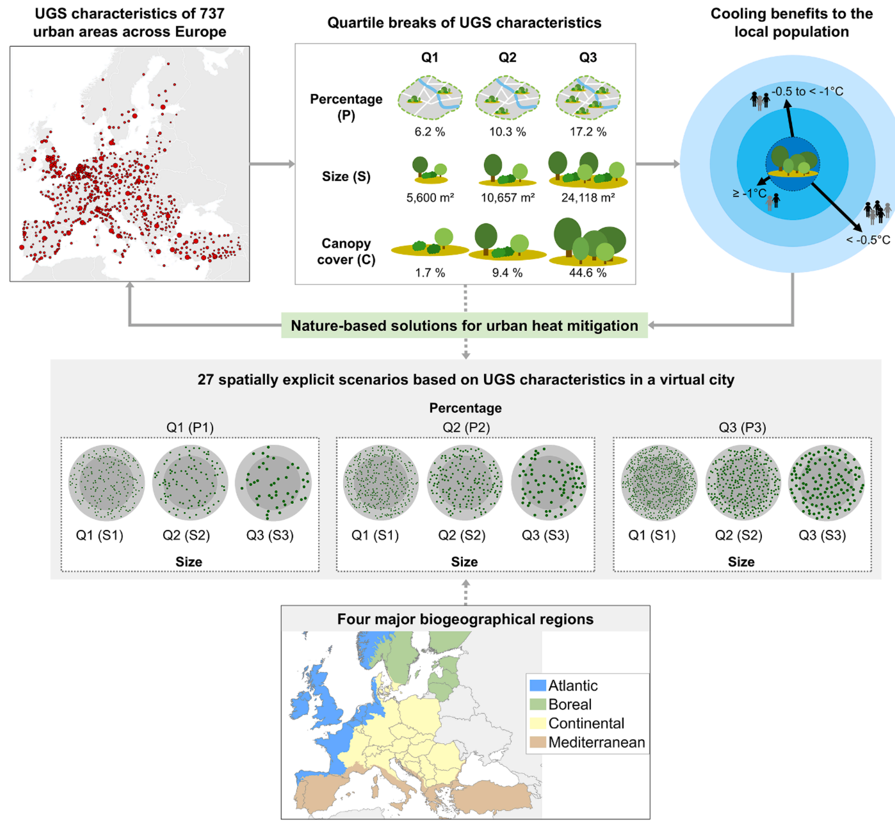

Fig. 2. Conceptual scheme to assess the influence of urban green spaces (UGS) on heat mitigation under 27 scenarios across four biogeographical regions using a virtual city. Scenarios are derived from the quartile breaks (Q1, Q2, Q3) of UGS percentage (P), size (S), and canopy cover (C) across European urban areas. Quartiles of canopy cover are not depicted in the spatial scenarios below. Cooling benefits are also evaluated by quantifying the share of population experiencing different levels of cooling. The virtual city comprises dense urban fabric (depicted in dark grey) and medium to low density urban fabric (depicted in light grey). Simulation of heat mitigation accounts for variations in input parameters across four major biogeographical regions.

across all UGS (n = 121,503) in Europe (Table S2), we defined 27 scenarios (Fig. 2, Table S3). For the nine different combinations of percentage and size, we created individual maps: We first determined the number of UGS to be placed within the virtual city (Table S4) and then randomly distributed them across the virtual city by creating random points as implemented in ArcGIS Pro 3.2 (ESRI, Redlands, CA, USA). To each point, we applied a specific buffer radius (Table S4) to create a polygon representing each UGS, corresponding to the quartile classes of UGS size. To make sure that the UGS did not overlap, we applied a minimum distance of at least 1 m greater than the respective diameter of the UGS.

Finally, we converted all scenario maps into raster data with a spatial resolution of 5 m to serve as input for the InVEST Urban Cooling Model (Integrated Valuation of Ecosystem Services and Tradeoffs, https://naturalcapitalproject.stanford.edu/software/invest, see section 2.2.2). For the scenarios that differed only in canopy cover, no additional maps were generated because changes in canopy cover were already included in the input parameters of the simulation model.

Analyzing the data

Characterizing European urban areas

To characterize European urban areas, we used the UGS percentage, size, and canopy cover of each urban area derived from the Copernicus Urban Atlas 2018 (see section 4.1.1). In addition, we quantified the number of people living in proximity to UGS in each urban area to assess patterns of benefits from UGS. In the Urban Atlas, population estimates are provided for individual urban fabric areas, which have been attributed to each polygon by downscaling or disaggregating census population counts [55]. We calculated a buffer zone of 250 m around each UGS polygon where UGS can be easily reached and cooling effects of UGS still may be perceived depending on their characteristics [33,34]. We overlaid the surrounding buffer zone with the urban fabric areas and derived the number of people residing within this area.

Across all urban areas, we calculated the quartiles of UGS characteristics, dividing the ranked dataset into four equal groups (each containing 25 % of the data) and mapped all characteristics to identify spatial patterns across Europe. We assessed differences in UGS characteristics across biogeographical regions [51] by assigning each urban area its respective biogeographical region and deriving mean values of UGS characteristics for each region. The original dataset contained nine terrestrial biogeographical regions, which we summarized into four major regions (i.e., Mediterranean, Continental, Atlantic, and Boreal; see Fig. 1), as only a few urban areas were located e.g., in Steppic or Arctic regions.

We assessed spatial autocorrelation by calculating the Moran's I index [56] using inverse Euclidean distance to evaluate whether the distribution of UGS characteristics was random or exhibited clustered spatial patterns that were influenced by similar characteristics in proximity. Since all UGS characteristics were spatially clustered (Table S5), we applied the multivariate clustering tool of ArcGIS Pro 3.2 (ESRI, Redlands, CA, USA) using the K-means algorithm to group urban areas with similar UGS characteristics. Based on the Calinski-Harabasz pseudo F-statistics, reflecting within-group similarity and between-group difference coefficient, we decided using the three-cluster solution, which divides the urban areas into three major groups.

Simulating heat mitigation

We applied the open-source model InVEST Urban Cooling Model (version 3.17.2) to estimate urban heat mitigation. The model quantifies how shade, evapotranspiration, and surface albedo, together with the spatial arrangement of vegetated and built areas, influence local air temperatures. Using land-cover data and biophysical coefficients for these three cooling mechanisms, the model calculates a spatially explicit Heat Mitigation Index (HMI) that represents the relative potential of each pixel to reduce air temperatures. Air temperature is then estimated by interpolating between a rural reference temperature and a user-defined UHI intensity. Because the model employs an index-based approach rather than a mechanistic energy-balance framework, its outputs represent relative cooling mitigation rather than physically explicit microclimatic temperature predictions. The InVEST Urban Cooling Model is a widely used tool to analyze the cooling effects of green infrastructure [57,46,58,41]. It has been validated with observational data in different contexts indicating generally good model performance [59,57,60,61]), though performing better for nighttime air temperatures but less during daytime [60]. The model is particularly suitable to assess relative differences across scenarios [60], which supports our aim to generally evaluate the influence of individual UGS characteristics on heat mitigation.

To assess variations in heat mitigation across the virtual city under 27 scenarios (Fig. 2), we calculated the HMI, which is estimated based on a combination of shade, evapotranspiration, and albedo. Evapotranspiration is represented through a normalized Evapotranspiration Index (ETI), calculated from land cover-specific crop coefficients and a reference evapotranspiration raster. The ETI expresses the relative evaporative cooling potential of each pixel and is combined with shade and albedo to estimate cooling capacity. Because the model operates on static land-cover inputs and does not simulate diurnal or seasonal dynamics, this output represents a single point in time per model run and depends entirely on the timestamp of the input land cover data and reference temperature values, while the spatial resolution corresponds directly to that of the input datasets. In this study, our focus was on daytime conditions during summer heat waves. We therefore set the air temperature predictor method to “factors”, i.e., shade, albedo, and evapotranspiration are used as temperature predictors for daytime temperatures. Accordingly, we prepared the following input data for the InVEST Urban Cooling model:

- **Reference evapotranspiration values**. We generated raster data for the virtual city based on average values for settlement areas derived from the CHELSA (Climatologies at high resolution for the earth’s land surface areas) repository, which provides global downscaled climate variables at a spatial resolution of about 1 km [62,63]. We distinguished reference evapotranspiration values across biogeographical regions and between dense versus medium- to low-density urban fabric to reflect major climatic and morphological differences (Table S6).
- **Crop coefficient Kc.** To derive the ETI, reference evapotranspiration values are combined with land-cover specific crop coefficients. We compiled mean Kc values for each land cover type and biogeographical region (Table S7). These values were based on the FAO-56 Irrigation and Drainage guidelines (Allen et al. [64], which provide standardized mid-season Kc values for representative vegetation categories and describe how climate modifies Kc through its influence on reference evapotranspiration and canopy resistance. Accordingly, higher Kc values were assigned to hot, dry Mediterranean climates, while lower values were assigned to Boreal regions.
- **Albedo**. The albedo factor represents the proportion of incoming solar radiation that is reflected by a given land cover type. Although albedo values of urban fabric tend to show limited variability [65], we assigned distinct average albedo values across biogeographical regions and land cover classes (Table S8) to account for regional differences in surface materials, urban geometry, and vegetation characteristics. These values were derived by combining findings from the literature (e.g., [49,66]).
- **Shade**. The shade factor represents the proportion of tree canopy (≥2 m in height) associated with each land cover type. In urban fabric, this factor was set to 0, because these areas generally lack substantial, spatially continuous canopy cover, and street-tree presence is highly variable across European cities, making it unsuitable to apply consistent shading values. In contrast, within UGS, the shade factor corresponds to the quartile breaks of canopy cover within UGS (see Tables 1, S1, and S2) as used in the scenarios, capturing their contribution to shading and daytime cooling.
- **Reference air temperature.** A heatwave is typically defined as a period of abnormally high temperatures relative to the local climate, usually based on temperature percentiles rather than fixed thresholds, e.g., at least three consecutive days exceeding the local 90th or 95th percentile of daily temperatures [15]. In the InVEST Urban Cooling Model, however, the reference air temperature does not influence the HMI itself, as it is calculated solely from biophysical factors (shade, albedo, and evapotranspiration) and is independent of temperature inputs. The reference air temperature affects only the final air temperature output, i.e., it shifts absolute temperatures but does not alter spatial patterns of cooling potential. For this reason, we used the same reference air temperature of the surrounding rural area of 30 °C across Europe, which aligns with the definition of a hot day [67].
- **Maximum UHI magnitude**. This parameter represents the temperature difference between the rural reference temperature and the maximum temperature observed in the urban area. For the daytime summer period (June to August), we estimated an average UHI intensity ranging between 2 °C and 5 °C across biogeographical regions (Table S9), based on an European-wide map representing simulations for 100 European cities (https://www.eea.europa.eu/en/analysis/maps-and-charts/the-average-summer-season-intensity).
- **Maximum cooling distance and air blending distance**. These two parameters influence how cooling effects propagate across the urban landscape, with the maximum cooling distance shaping the spatial reach of vegetation-driven mitigation and the air-blending distance determining the degree of atmospheric mixing incorporated into the final temperature estimates. According to the recommendations from the InVEST user guide [68], the maximum cooling distance and air blending distance were set to 450 and 500 m, respectively.
- **Average relative humidity**. Mean summer relative humidity (%) for each biogeographical region (Table S9) was extracted from the CHELSA repository [62,63], which provides monthly time series of spatially enhanced relative humidity for Europe at 1 km resolution.

We simulated cooling effects using the InVEST Urban Cooling Model within the virtual city. We calculated 27 scenarios across four biogeographical regions, resulting in a total of 108 simulations. Please note that model validation and calibration of the model parameters were not performed due to the virtual setting. The model generated several outputs used for subsequent analyses, including the HMI and air temperature, provided both as spatially explicit maps and as average values for the entire virtual city.

We estimated the number of people potentially benefiting from the heat mitigation effects of UGS by deriving the average population density of dense as well as for medium to low density urban fabric from the population estimates of the Urban Atlas data. We created a regular grid of buildings with a size of 20×20 m across the virtual city and assigned the average number of people to each grid cell, distinguishing between dense and medium to low density urban fabric (Table S10). The InVEST urban cooling model provided the average temperature for each building, which we used to quantify the number of people benefitting from a temperature decrease of < -0.5 °C, -0.5 to < -1 °C, and ≥ -1 °C, respectively.

Results

Characteristics of urban green spaces in European urban areas

UGS characteristics greatly differed across the 737 urban areas with distinct spatial patterns (Fig. 3; Table S1 for individual urban areas). While urban areas with an above-average percentage of UGS were mostly located in northern and western Europe, those located in southeastern Europe had more often a below-average percentage of UGS, e.g., in Romania, Slovenia, and Turkey. Larger UGS were mostly located in central and northern Europe, while small UGS were found mostly around the Mediterranean, especially in Turkey, Greece, Italy, and Spain. The canopy cover within UGS showed less distinct spatial patterns across Europe. UGS in eastern and northern regions of Europe were generally characterized by low canopy cover compared to those located in central and southern Europe. Contrasting trends were also found for the population in proximity to UGS between northwestern and southeastern Europe, indicating an unequal distribution of benefits by UGS particularly in Turkey, Romania, Balkan countries, southern Italy, and Portugal.

Comparing European biogeographical regions, UGS characteristics significantly differed mostly for size and percentage (Fig. 4). Urban areas located in the Boreal performed on average best in size (15,529 m^2) and percentage (21.2 %), followed by the Continental (size: 11,976; percentage: 9.1 %) and Atlantic (size: 11,583; percentage: 11.1 %). In contrast, urban areas located in the Mediterranean were characterized by the smallest size (8304 m^2) and least percentage (9.7 %). Canopy cover within UGS was highest in the Mediterranean (13.9 %) and lowest in the Boreal (6.3 %). The share of population residing in proximity to UGS was highest in the Boreal (52.7 %) but lowest in the Mediterranean (47.1 %). For individual urban areas, see Table S1.

Heat mitigation effects of scenarios in a virtual city

Across all biogeographical regions, the simulation results of the 27 scenarios in the virtual city indicate clear and consistent patterns of cooling effects in relationship with increasing percentage, size, and canopy cover of UGS at the city-wide level (Fig. 5, Figure S1). The HMI significantly increased as canopy cover increased and, to a slightly lesser extent, as the percentage of UGS increased. The strongest effects occurred when both the percentage of UGS and the canopy cover within UGS increased simultaneously. On average, an increase from P1-C1 to P3-C3 led on average to an increase in the HMI of 37.3 % ($p < 0.001$) and a decrease of −0.5 °C, regardless of changes in size. Relative increases in HMI values between the P1-S1-C1 and P3-S3-C3 scenario were highest in the Boreal (+42.3 %), followed by the Atlantic (+37.4 %) and the continental (+35.6), and lowest in the Mediterranean (+33.9 %). However, the absolute temperature decrease was highest in the Mediterranean (Figures S1 and S2), where all classes and scenarios exhibited pronounced cooling, ranging between −0.54 and −0.98 °C. The Atlantic region showed similarly strong but slightly less pronounced effects, with average temperature decreases around −0.39 to −0.73 °C. In contrast, cooling effects in the Continental region were markedly weaker, with values around −0.31 to −0.56 °C. The smallest cooling effects occurred in the Boreal region overall, ranging from −0.18 to −0.33 °C across all scenarios.

The maps further revealed local variability in cooling effects in relation to the concentration and distribution of UGS, indicating that cooling effects exceeded UGS in zones of high UGS concentrations for scenarios with a high percentage of UGS and high canopy cover within

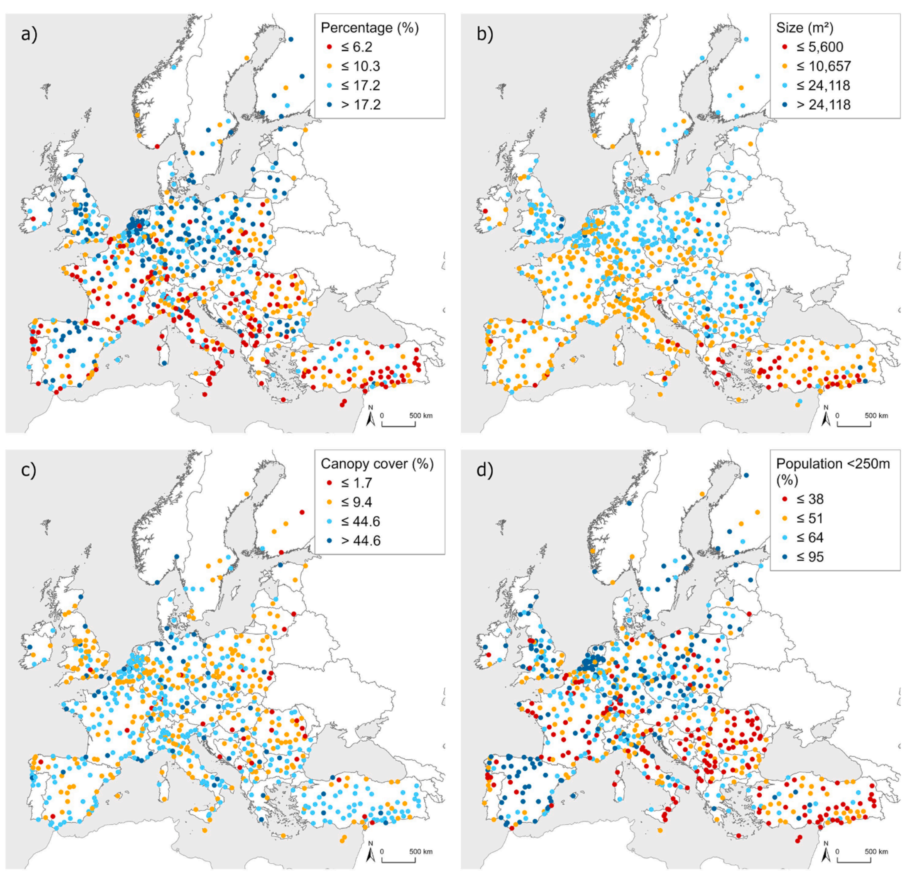

Fig. 3. Distribution of UGS characteristics (a, b, c) and share of the population living at <250 m **to UGS** (d) across European urban areas**. Map c**lass breaks reflect quartile breaks across European urban areas. For country locations, see Fig. 1. Data have been derived from Copernicus Urban Atlas 2018 (https://land.copernicus.eu/local/urban-atlas).

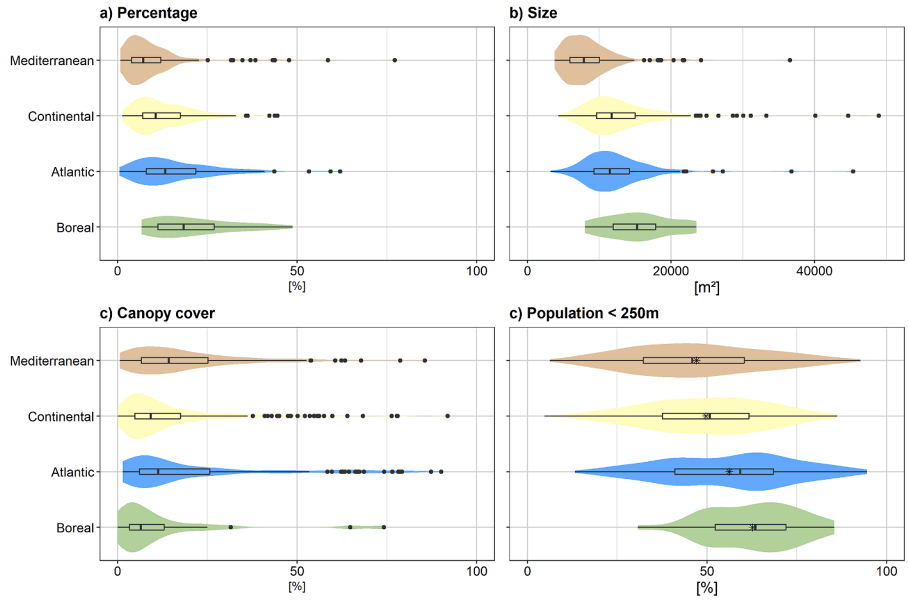

Fig. 4. Violin plots of UGS characteristics (a, b, c) and share of the population living at <250 m **to UGS** (d) across European urban areas distinguished by biogeographical region (see Fig. 1). Data have been derived from Copernicus Urban Atlas 2018 (https://land.copernicus.eu/local/urban-atlas).

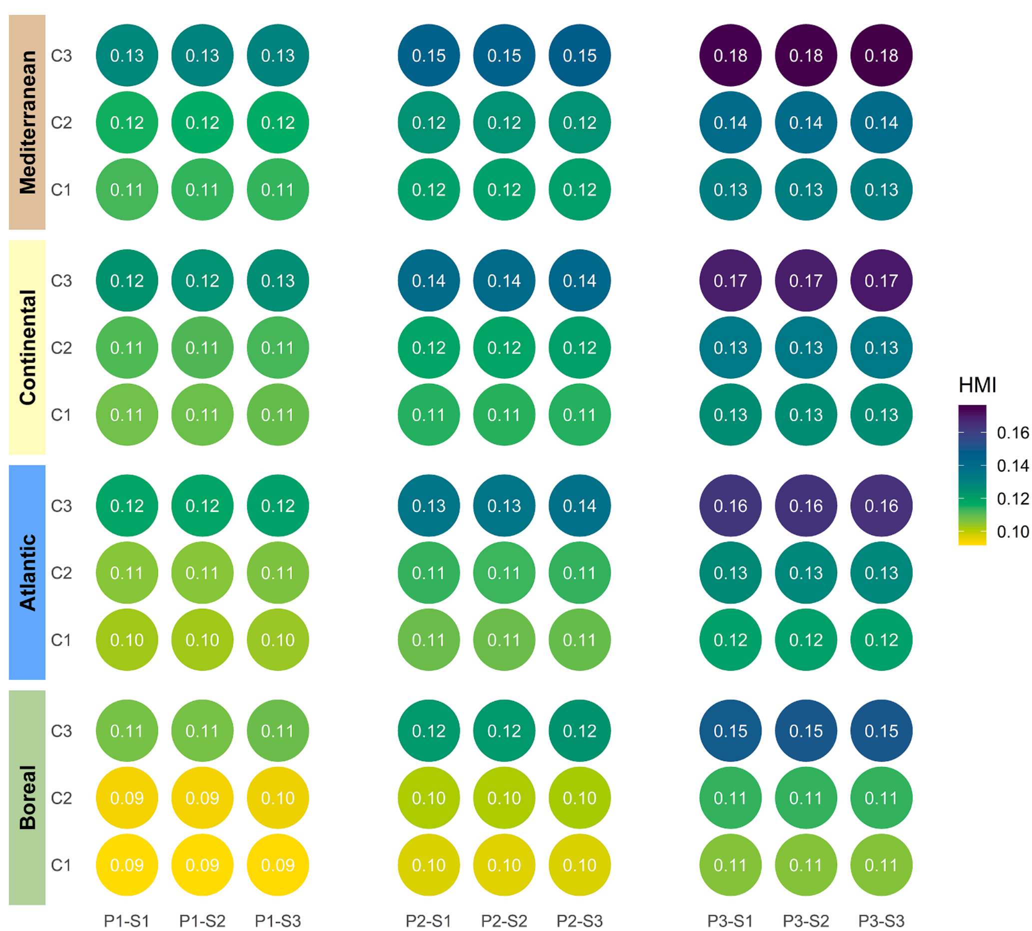

Fig. 5. Average heat mitigation index (HMI) under 27 scenarios (see Fig. 2 and Table S3) based on UGS percentage (P), size (S), and canopy cover (C) for four major biogeographical regions (see Fig. 1), reflecting quartile breaks (Q1, Q2, and Q3) across European urban areas. The HMI reflects the relative potential of each pixel to reduce air temperature given that scenario's spatial configuration of UGS.

UGS (P3-C3; Figure S3). Such patterns were also evident in relation to the number of people potentially benefiting from different levels of local temperature decrease in regions with higher cooling effects (Fig. 6). While in regions with low cooling effects (i.e., Boreal and Continental

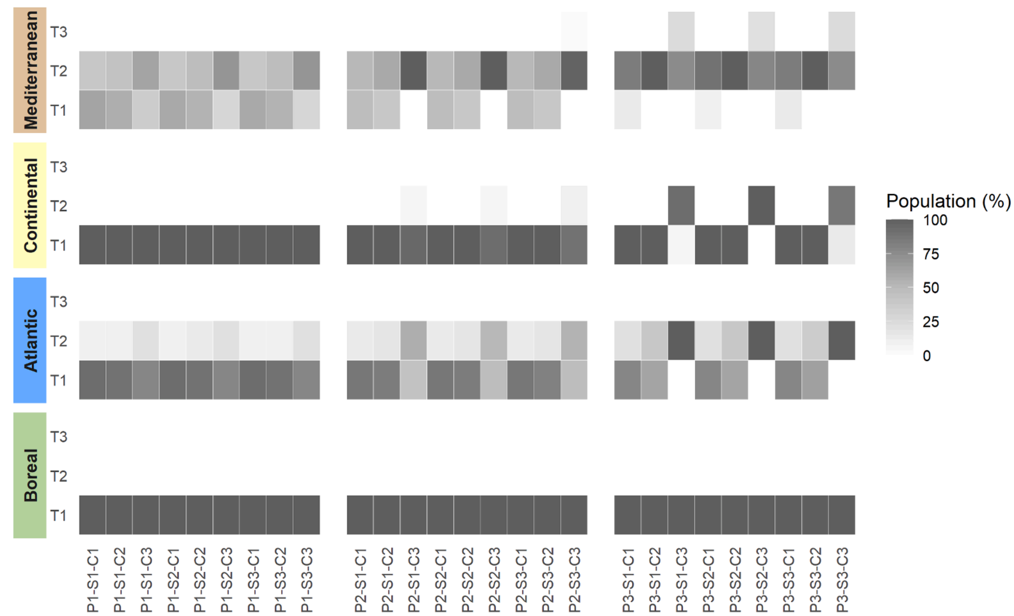

Fig. 6. Share of population benefiting from different levels of cooling effects under 27 scenarios based on UGS percentage (P), size (S), and canopy cover (C) for four biogeographical regions (see Fig. 1), reflecting quartile breaks (Q1, Q2, and Q3) across European urban areas (see Fig. 2 and Table S3). T1 represents a temperature decrease of < −0.5 °C, T2 a decrease from −0.5 to < −1 °C, and T3 a decrease of ≥ −1 °C.

regions), close to 100 % of the population typically experienced only temperature decreases of up to −0.5 °C. In the Atlantic and Mediterranean regions, a higher share of the population benefited from a higher temperature decrease, ranging between −0.5 to −1 °C. Particularly, the increase in canopy cover within UGS was consistently related to a higher share of people benefitting from stronger cooling effects.

Potential of enhancing UGS in European urban areas

To identify general patterns in UGS characteristics across Europe, we grouped the urban areas based on percentage, size, canopy cover, and population in proximity to UGS, resulting in three major groups of urban areas with distinct patterns (Fig. 7). Group 1 ($n = 280$) was characterized by the highest percentage of UGS (95.4 % of the urban areas in this group were above average) and highest share of population living in proximity to UGS (97.1 %). Urban areas belonging to Group 2 ($n = 365$) had the lowest percentage (81.2 % below average) and the smallest size (63.5 % below average), while 57.9 % of the urban areas had above-average canopy cover. Group 3 ($n = 110$) performed best in terms of size (63.5 % above average) but worst in canopy cover (38.8 % below average) and share of population (31.5 % below average). Also, 67.3 % of the urban areas of this group were below average regarding the percentage of UGS. Group 2 consistently comprised most urban areas of the Mediterranean and Continental regions, while Group 1 was more important in the Continental and Atlantic regions (Figure S4). Group 3 had only a moderate share in the Continental region but were less important in the other regions.

Accounting for the simulation results in the virtual city, the highest potential for increasing cooling effects through UGS occurs for urban areas belonging to groups 2 and 3 (Figure 7; Table 2). Here, an increase in the percentage of UGS together with increasing canopy cover could significantly reduce city-wide average air temperatures up to −0.44 °C in the Mediterranean urban areas and up to −0.34 °C in the Atlantic urban areas (Figure S1). Urban areas of group 3 also have considerable

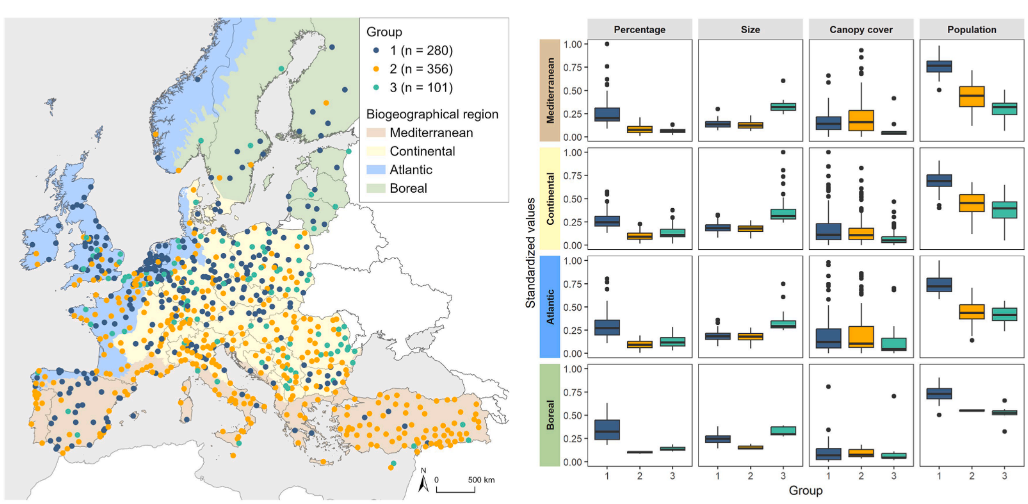

Fig. 7. Groups of urban areas identified through cluster analysis based on UGS percentage, size, canopy cover, and the share of population in proximity to UGS (left); differences in UGS characteristics across these groups distinguished by biogeographical region (right).

Table 2
Percentage of urban areas in each quartile comprised in the groups identified through cluster analysis, distinguished by biogeographical region relative to all European urban areas ($n = 737$).

UGS characteristic	Group	Quartile	Mediterranean	Continental	Atlantic	Boreal	Total
Percentage	1	1	-	-	-	-	-
		2	0.9	0.1	0.7	-	1.8
		3	2.3	5.7	3.9	0.4	12.3
		4	2.6	10.9	8.1	2.3	23.9
	2	1	10.4	7.9	3.3	-	21.6
		2	5.6	8.0	3.7	0.4	17.6
		3	3.4	3.3	2.2	-	8.8
		4	-	0.3	-	-	0.3
	3	1	1.1	1.5	0.8	-	3.4
		2	0.3	3.9	1.1	0.5	5.8
		3	-	2.4	0.8	0.4	3.7
		4	-	0.7	0.1	-	0.8
Size	1	1	0.9	0.1	0.3	-	1.4
		2	8.1	14.9	10.9	0.8	34.7
		3	2.4	27.3	21.2	6.9	57.8
		4	-	-	-	-	-
	2	1	4.2	0.3	0.1	-	4.6
		2	25.0	18.5	8.1	0.5	52.1
		3	8.1	29.7	14.7	0.4	52.9
		4	-	-	-	-	-
	3	1	-	-	-	-	-
		2	-	-	-	-	-
		3	3.3	21.2	6.9	2.8	34.2
		4	1.1	6.0	2.2	-	9.2
Canopy cover	1	1	0.4	0.3	0.1	0.4	1.2
		2	1.5	6.2	4.2	1.1	13.0
		3	3.5	7.9	5.8	0.8	18.0
		4	0.3	1.6	1.6	0.1	3.7
	2	1	0.4	0.9	0.1	-	1.5
		2	5.0	8.5	3.4	0.3	17.2
		3	11.4	8.7	3.3	0.1	23.5
		4	1.9	1.1	1.5	-	4.5
	3	1	-	1.1	-	0.1	1.2
		2	1.1	5.0	1.6	0.5	8.3
		3	0.3	2.0	0.7	0.1	3.1
		4	-	-	0.3	0.1	0.4
Population	1	1	4.9	10.7	10.3	2.4	28.4
		2	0.8	5.2	2.4	0.1	8.5
		3	0.1	0.8	-	0.1	1.1
		4	-	-	-	-	-
	2	1	1.2	0.1	0.3	-	1.6
		2	4.7	6.4	2.0	0.4	13.6
		3	6.4	6.9	4.3	-	17.6
		4	7.1	6.0	2.4	-	15.5
	3	1	-	-	-	0.1	0.1
		2	-	1.5	0.5	0.4	2.4
		3	0.3	3.3	1.4	0.3	5.2
		4	1.1	3.8	0.9	0.1	6.0

potential in improving heat mitigation by increasing both the percentage and canopy cover of UGS, however, a more equal spatial distribution of UGS across the urban area is needed to also increase the share of population that could benefit from cooling effects. For group 1, cooling effects may still be improved by increasing the canopy cover within UGS.

Discussion

Improving the effectiveness of urban green spaces in urban areas across Europe

Given the current and anticipated impacts of heat waves, together with the new EU nature restoration law, scientists, decision makers, and planners increasingly seek information on how to maximize the effectiveness of NbS [2,3,17]. By characterizing European urban areas and evaluating the cooling influence of three UGS characteristics by simulating heat mitigation under different scenarios in a virtual city, we found consistent patterns across all biogeographical regions. Although relative differences in HMI values were more pronounced in the Atlantic and Boreal urban areas due to enhanced cooling capabilities of UGS, the decrease of city-wide temperatures was noticeably stronger in the Mediterranean and Continental urban areas, where canopy cover through shading seems to have greater cooling effects than evapotranspiration [50].

Overall, our findings indicate that the percentage of canopy cover within UGS is the most influential factor in mitigating urban heat among the three characteristics tested. This is in line with previous studies demonstrating that high canopy cover provides both shade and higher cooling effects [28,69,70,32], while sparsely vegetated UGS may dry up more quickly. Especially under intense and long-lasting heat waves, UGS without or with little canopy cover may lose their cooling capacity and hence contribute to further temperature increase [9,71]. Our analysis of European urban areas revealed that UGS canopy cover reached only 9.4 % in half of the urban areas, while studies recommend having at least 16 % UGS canopy cover to reduce the temperature by about 1 °C [27]. Higher cooling effects can be achieved by further increasing canopy cover towards urban forests [72,33,37]. The first heat mitigation measure is, therefore, increasing canopy cover within UGS. Although we found minor differences across Europe, urban areas located in the northern parts of Europe (Boreal region) or belonging to group 3 had on average low canopy cover, and thus, still have the potential to increase cooling effects by increasing the canopy cover. Consequently, urban planners and managers should prioritize the integration of trees into UGS design, accounting for vegetation structures and crown quality to improve cooling effects [31,73].

Our findings indicate that the increase in percentage of UGS is the second most influential factor on heat mitigation. These findings align with previous studies [33,34] and suggest that urban areas could adapt more effectively to the projected increase in heat waves by converting sealed surfaces into unsealed UGS [69]. Our analysis of European urban areas revealed distinct spatial patterns consistent with other studies [74,48,75], indicating that urban areas in southeastern Europe (group 2) had less than half of the percentage of UGS compared to those in northern regions. While such differences can be attributed to specific cultural, historical, social, and environmental contexts [76], they have important implications for urban planning in southern and eastern European urban areas (groups 2 and 3). In these areas, the UGS percentage should be considerably increased, possibly to >17.2 %, to achieve cooling effects from UGS. However, it should be noted that the implementation of new UGS often competes with other lucrative land uses, and available space may be limited [43]. Moreover, UGS must be carefully planned, as cooling effects in warmer and dryer urban areas, e.g., located around the Mediterranean, depend on vegetation characteristics and water availability [77].

Studies agree that the cooling of air temperatures is limited to relatively narrow zones around UGS, though larger UGS generate greater cooling effects that can extend several hundreds of meters beyond the park limits dependent on further factors such as relief and corridors for cold air flows [36,33,34,37]. However, there is less evidence that small UGS contribute to heat mitigation [31]. Our findings suggest a positive influence of small UGS on heat mitigation, depending on the spatial concentration and overall percentage of UGS, while UGS size had no significant influence on urban heat mitigation at the city-wide level. An explanation may be that the size in the scenarios was very small for S1 (0.56 hectares) and S2 (1.07 hectares), representing three-quarters of UGS across European urban areas. Only for S3, it reached 2.4 hectares. In the InVEST model, 2 hectares are considered a threshold between small and large parks, and the model attributes only to large parks an additional cooling effect that goes beyond the UGS limits [37]. Moreover, our analysis targeted city-wide heat mitigation under controlled, virtual conditions, aggregating outcomes across the entire urban extent. In contrast, many studies emphasizing park size effects examine local cooling intensity and decay with distance from an individual park.

Considering justice in nature-based solutions

Despite increasing consideration of environmental justice, the implementation of NbS still insufficiently accounts for potential inequities in the spatial distribution of beneficiaries and their specific needs for heat mitigation [78,44]. Accordingly, our maps (Figure S3) revealed great local differences in heat mitigation, which was also reflected in the share of people benefiting to a different extent from cooler temperatures. Across Europe, we found greatest disparities in benefits in urban areas belonging to groups 2 and 3, where more than two-thirds of the population live at distances greater than 250 m away from UGS. These findings emphasize the need to address issues related to justice when implementing NbS [39,44,40]. Moreover, socially vulnerable people often live in neighborhoods with limited access to UGS, where creating or improving green infrastructure for heat mitigation is highly needed [5,45].

There are other characteristics of UGS that also relate to social justice. UGS are multifunctional areas providing many environmental, social, health, and economic co-benefits [79–81]. For example, UGS can contribute to several provisioning and regulating services including air quality improvement, noise mediation, flood mitigation, carbon sequestration, as well as provide various cultural ecosystem services such as opportunities for recreation, aesthetic experiences, education, and inspiration [82–84]. People also particularly value non-material benefits such as the improvement of physical and mental health, social relationships, and sense of place [85]. Thus, UGS should account for people's needs and preferences living in the surrounding neighborhoods, which, however, often differ among social groups [86,85,87]. For example, elderly people may prefer quieter UGS and appreciate amenities such as sufficient seating places and barrier-free access, whereas young people may value higher opportunities for social interaction as well as sports facilities. To integrate differing demands and interests, decision-makers and planners should include all residents into the UGS planning and decision process through participatory approaches that acknowledge values and preferences of different socio-cultural groups and help anticipating potential conflicts [88–90].

Challenges and limitations related to the implementation of nature-based solutions in urban areas

Our findings suggest that extending the percentage of UGS in urban areas, combined with increasing canopy cover within UGS, is an effective strategy for mitigating future heat waves. However, there are also various constraints related to the implementation of new UGS. These include, for example, limited availability of space, insufficient financial resources, unequal distribution of ownership, and competing interests [91]. Increasing the canopy cover may therefore be the first option in many places. While several cities in southern Europe have on average extremely high canopy cover, for example, Nice in France (85.6 %), Massa in Italy (78.7 %), and Zonguldak in Turkey (67.8 %), there are also many cities that have <9.4 % (C2) of canopy cover. In northern countries, many urban areas have the potential to increase canopy cover, in particular Vilnius in Lithuania, Daugavpils in Latvia, as well as Helsinki in Finland which have all <1.7 % (C1) of canopy cover.

However, cooling effects not only depend on the amount of canopy cover but also on the crown quality and shape measured, for example, by leaf area density and vitality [73]. Moreover, measures for increasing urban greenery need to be carefully evaluated for not creating or aggravating conflicts among uses of resources or disbenefits to people related to plant species or blue-green infrastructure. In northern regions, for example, a higher canopy cover may lead to higher risks under heavy storms or snowfall due to the risk of branches breaking [92], while considering water needs for irrigation in water-scarce regions such as in Mediterranean and Continental cities is key, particularly in the light of climate change and precipitation unpredictability. To avoid trade-offs that undermine water security or housing needs, this requires the implementation of strategies to reduce water consumption, e.g., by using efficient irrigation systems such as sensor-based watering, greywater reuse, and rainwater harvesting, by adopting flexible irrigation plans in dependence on the season and weather situation, and by selecting local and drought tolerant species that can better scope with water stress or treated wastewater [93]. Furthermore, integrating green, blue, and grey infrastructure to capture and reuse stormwater can create reserves for sustaining vegetation during dry periods. However, it also needs to be considered that an increase in urban greening may facilitate the emergence and spread of mosquitoes and vector-borne diseases, requiring adequate water management [94].

Cooling effects of UGS are also influenced by further factors including, for example, vegetation composition and structure within UGS [30–32], as well as urban morphology, land cover, and local climate zone, affecting shading, air movement, and urban microclimate [69,47,70,50,95]. Climate conditions also influence the cooling capacity of vegetation during heat waves depending on irrigation practices [96] as well as on the intensity, duration, and frequency of heat waves, potentially impacting the vegetation and their recovery after extreme events [97,98]. Therefore, it is particularly important to select vegetation types and plant species that are adapted to the local climate and that can cope with future climate conditions.

Since space for creating new UGS is often limited, designing UGS that coexist with housing and infrastructure can create multifunctional spaces. For example, green infrastructure such green roofs, facades, walls, schoolyards, and courtyards that fit into dense urban fabrics [99–101], or street tree coverage [102,103], may be easier to implement in city centers and does not compete with living spaces. Another solution is integrating UGS into redevelopment projects transforming underused or obsolete urban spaces into multifunctional green areas rather than expanding UGS into areas needed for housing. Suitable sites withing and around urban areas that can be redesigned into eco-districts with integrated parks, gardens, and green corridors, mitigating climate change impacts, include, for example, old industrial or underused sites, brownfield sites, and road and rail infrastructure [104,105].

Methodological limitations

Our results highlight differences across European urban areas as well as the potential effects and interactions of UGS characteristics on urban heat mitigation, but there are also several limitations. Regarding the quantification of the benefiting population across the European urban areas, only based on proximity to UGS, disregards differences in vulnerability to heat of socio-demographic groups [3,5,6]. Therefore, the integration of social vulnerability indices or demographic information would provide deeper insights, which should be addressed by future studies. Most limitations, however, are related to the scenarios. First, the InVEST urban cooling model comes along with a series of constraints and simplified assumptions, such as uncertainty in the weighting of shade, albedo, and evapotranspiration, generalized assumptions on cooling effects beyond park boundaries, linear relationship between canopy cover and cooling effects, and disregarding shading by buildings [54,60,37]. Many of these issues (e.g., weighting of parameters) are less relevant for our study, because keeping all parameters constant across the scenarios except for one parameter allows for comparing relative values. However, the extent of change between the individual scenarios may not be underestimated or overestimated, for example, due to the differentiation between small and large UGS and related assumptions regarding the distances of cooling effects beyond UGS boundaries. Although we addressed bioclimatic differences by integrating biogeographical regions, the absolute temperature changes reported in our results need to be interpreted with caution, as they represent average values. These values will likely differ in real urban areas with more specific climatic and morphological characteristics, as local cooling effect greatly depend on vegetation properties, local climate, and wind patterns, as well as the structure and morphology of adjacent buildings and terrain [106,37]. For real-world assessments, the model parameters (shade, evapotranspiration, and albedo) should be validated with empirical data and calibrated with local conditions to best fit measured temperatures [57,60].

Similarly, our findings regarding the population living in proximity to UGS differ in real-world cities with distinct urban morphologies and socio-demographic inequities. While we assumed an equal distribution across the virtual city of buildings and residents, in real cities not only the population density varies across urban districts, but also groups with higher vulnerability to heat are often concentrated in disadvantaged neighborhoods [107]. Here, the assessment of distance-related gradients of cooling effects from UGS would provide more specific insights (e.g., [37]). Nevertheless, our results emphasize the importance of assessing cooling effects at different spatial levels across cities to address issues of justice. Another constraint is the focus on UGS in our study, while urban heat mitigation can be achieved through further elements of green, blue, and grey infrastructure such as street trees, green roofs, and walls, or rivers, lakes, and ponds [99,101,25,102,22,108]. For example, calculating canopy cover relative to the total urban area could provide insights into broader city-wide cooling potential, particularly in cities where tree canopy outside UGS, such as along streets or within built-up courtyards, contributes substantially to shading and evapotranspiration [49]. This was beyond the scope of our study, and further research is necessary to assess interactions among different types of such infrastructure as well as diurnal variations to evaluate the potential of UGS and improve their effectiveness in urban heat mitigation [109].

Our findings provide insights into large-scale patterns and generalized trends across Europe, which serve as a benchmark across European urban areas by comparing the deviation of individual urban areas (Table S1) to the average values across Europe. However, there are limitations in transferring our simulation results to specific contexts. First, focusing on the quartiles of UGS characteristics across all urban areas does not depict the complete spectrum of possible configurations. Future studies should therefore derive extreme scenarios based on minimum and maximum values of UGS characteristics. Moreover, it was not possible to fully account for relationships between geographical locations, size of urban areas, number and characteristics of UGS [27]. In future studies, such simulation exercise could be refined by distinguishing distinct typologies of cities, for example, based on size, building density and height, topography, and surrounding land cover. This could be achieved through a clustering approach that integrates urban morphology, climate types, and UHI profiles, followed by the design of a representative virtual city for each cluster. Such an approach would greatly enhance the generalizability of the results. More specific scenarios results could also be obtained by adapting the model parameters (i.e., shade, evapotranspiration, and albedo) based on species traits reflecting, for example, crown quality [73]. In addition, it is necessary to assess differences of cooling effects between daytime and nighttime [109], as well as to account for variations in UHI effects across cities to indicate the specific cooling potential by UGS [11]. Since European countries have different climates, regional variations in UGS can be captured by characterizing urban areas within distinct climate zones (e.g., Mediterranean, continental, oceanic). This approach could also enable transferring the findings to cities outside Europe. Nevertheless, to provide reliable guides for real urban planning and heat mitigation strategies, scenarios need to be tested within the specific urban context due to the complex interactions of multiple factors influencing cooling effects of UGS [27].

Conclusion

To support decision-making and planning in addressing the future increase in heat waves, this study combined an analysis of UGS characteristics across 737 urban areas in Europe with heat mitigation simulation of 27 scenarios using a virtual city. Our analysis revealed consistent, large-scale patterns and generalized trends across major European biogeographical regions, providing a benchmark for European urban areas by comparing individual cities' deviations from average UGS characteristics. Overall, our findings highlight the need to implement new or improve existing UGS across European urban areas, while indicating potential adaptation measures based on the simulations. For example, people living in southern and eastern European urban areas will mostly benefit from expanding UGS and achieving a more even distribution of UGS across the urban area. While northern regions generally have a greater percentage of UGS, there is still some potential to increase cooling effects by increasing the canopy cover. Nevertheless, simulation results should be validated against empirical temperature data. Additional scenarios must also be tested in specific urban contexts to account for the complex interactions among multiple factors influencing UGS cooling effects. This will ensure reliable guidance for urban planning and heat mitigation strategies in real-world cities.

Impacts and implications

- **Environmental concerns:** The study addresses the potential of heat mitigation caused by climate change in European urban areas through nature-based solutions, contributing to an enhanced understanding of the influence of the characteristics of urban green spaces in terms of percentage, size, and canopy cover on cooling effects.

- **Economic concerns**: Mitigating urban heat through nature-based solutions contributes to energy savings. The study focuses on the heat mitigation index, but energy savings are strongly correlated. Therefore, our findings provide a basis for the quantification of economic savings.
- **Social concerns:** We assess issues of environmental justice by quantifying the share of population residing in proximity to urban green spaces across European urban areas, as well as by analysing the share of population benefitting from different levels of cooling effects under nature-based solution scenarios.

CRediT authorship contribution statement

Uta Schirpke: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Alberto González-García:** Writing – review & editing, Conceptualization. **Sandra Rome:** Writing – review & editing, Conceptualization. **Ignacio Palomo:** Writing – review & editing, 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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2026.100321.

Data availability

Data will be made available on request.

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