Science of the Total Environment 922 (2024) 171215

Contents lists available at ScienceDirect

Science of the Total Environment

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

Ecosystem service mismatches evidence inequalities in urban heat vulnerability

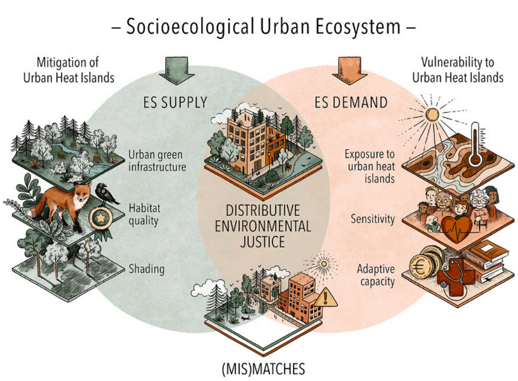
Celina Aznarez [a,b,*], Sudeshna Kumar [b], Alba Marquez-Torres [b], Unai Pascual [b,c], Francesc Baró [d,e]

[a] *Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona, Cerdanyola del Vallès, Spain*
[b] *Basque Centre for Climate Change (BC3), Leioa, Spain*
[c] *Basque Foundation for Science, Ikerbasque, Bilbao, Spain*
[d] *Department of Geography, Vrije Universiteit Brussel (VUB), Brussels, Belgium*
[e] *Department of Sociology, Vrije Universiteit Brussel (VUB), Brussels, Belgium*

HIGHLIGHTS

- We assess disparities in heat vulnerability and its environmental justice implications
- We model temperature regulation ecosystem service supply-demand mismatches
- Heat exposure is higher in socio-economically disadvantaged communities
- Affluent areas exhibit lower mismatches, suggesting reduced heat vulnerability
- Nature-based heat mitigation interventions should focus on socio-economically disadvantaged communities

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paulo Pereira

Keywords:
Urban heat island
Ecosystem services mismatch
Vulnerability
Environmental justice

ABSTRACT

Exposure to heat poses a pressing challenge in cities, with uneven health and environmental impacts across the urban fabric. To assess disparities in heat vulnerability and its environmental justice implications, we model supply-demand mismatches for the ecosystem service (ES) urban temperature regulation. We integrated remote sensing, health, and socio-demographic data with Artificial Intelligence for Environment and Sustainability (ARIES) and geographical information system tools. We computed composite indicators at the census tract level for urban cooling supply, and vulnerability to heat as a measure of demand. We do so in the context of the mid-size city of Vitoria-Gasteiz, Basque Country (Europe). We mapped relative mismatches after identifying and analysed their relationship with socio-demographic and health factors. Our findings show disparities in heat vulnerability, with increased exposure observed among socio-economically disadvantaged communities, the elderly, and people with health issues. Areas associated with higher income levels show lower ES mismatches, indicating higher temperature regulation supply and reduced heat vulnerability. The results point at the need for

* Corresponding author at: Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona, Cerdanyola del Vallès, Spain.
E-mail address: Celina.Aznarez@autonoma.cat (C. Aznarez).

https://doi.org/10.1016/j.scitotenv.2024.171215
Received 22 November 2023; Received in revised form 23 January 2024; Accepted 21 February 2024
Available online 28 February 2024

nature-based heat mitigation interventions that especially focus on the more socio-economically disadvantaged communities.

1. Introduction

Over the past decades, heatwaves have increased in frequency, intensity, and duration (Cowan et al., 2014; Fischer and Schär, 2010), with expectations of further intensification due to accelerated global warming (Ballester et al., 2023). Urban areas are particularly vulnerable to rising global temperatures due to the urban heat island (UHI) effect, which results in substantially higher temperatures in dense urban environments compared to suburban-rural areas (Marando et al., 2022; Massaro et al., 2023). The synergistic effects of heatwaves and UHIs affects human health and the urban environment (Grimm et al., 2008; Chen et al., 2023), constituting a major hazard for urban residents with far-reaching health and well-being impacts (IPCC, 2021; Kuras et al., 2015). For instance, elevated urban temperatures can reduce work productivity, impair cognitive performance and learning capacity (Lenton et al., 2023), while also contributing to increased morbidity, mortality rates, and maternal health risks (Ballester et al., 2023; Lenton et al., 2023).

With the expansion and densification of urban environments, there is a an increased interest in the provision of urban ecosystem services (ES) (Liu et al., 2020) through the implementation of urban green infrastructure strategies, particularly regarding urban heat mitigation (Francoeur et al., 2021; Langemeyer et al., 2020; Wolch et al., 2014). Urban green infrastructure (UGI) helps reduce land surface and air temperatures during hot periods by providing shade, limiting the absorption of solar radiation in artificial surfaces, and promoting evapotranspiration (Errea et al., 2023; Massaro et al., 2023).

Urban development shapes the distribution and balance between green and grey infrastructure, influencing heat absorption and release (Schell et al., 2020; Marando et al., 2019). Inequities in exposure and access to UGI and associated ES can also be driven by socioeconomic and urban planning factors whose interaction further exacerbate disparities (Aznarez et al., 2023; Baró et al., 2019). A key contributing factor to these disparities is the 'legacy effect', where historical management practices contribute to increased canopy cover and plant diversity in older neighbourhoods, reflecting extended successional times (Clarke et al., 2013). To illustrate, areas that historically received more attention and investment in UGI development accumulate greater biodiversity, perpetuating environmental disparities. This 'legacy effect' intersects with the 'luxury effect', linking affluence to increased canopy cover and biodiversity. Affluent areas, historically benefiting more from UGI development, experience cumulative impacts over time (Leong et al., 2018). These disparities compound, hindering equitable provision of urban temperature regulating ecosystem service (TR-ES) and perpetuating 'luxury effects' on canopy cover and its related benefits (Jenerette et al., 2013). In turn, this can contribute to a complex mosaic of temperatures within cities that may expose residents to a *continuum* of heat, ranging from thermal comfort to potential hyperthermia (Lenton et al., 2023; Jenerette et al., 2011). Social inequities amplify heat-related disparities and their health implications, particularly among socioeconomically disadvantaged communities (Wang et al., 2023; Schell et al., 2020; Chakraborty et al., 2019).

Equitable access to UGI for mitigating heat vulnerabilities requires evaluating the distribution of the supply of TR-ES and the societal demand for such ES. We refer to 'supply' as the capacity of urban ecosystems to provide TR-ES, and 'demand' as the societal need to reduce heat-related vulnerability and risk through UGI (Burkhard and Maes, 2017). Despite increasing recognition, understanding and mapping ES demand remain challenging due to this multifaceted nature, influenced by factors like access, technological influences, socio-economic conditions or demographics (Dworczyk and Burkhard, 2021; González-García et al., 2020). Unlike traditional ES assessments that rely on indirect inferences of demand by considering the magnitude of pressures and assessing the population exposed to these pressures (Baker et al., 2021; Wolff et al., 2015), our research integrates the multifaceted character of demand. We contribute to addressing this gap by integrating the demand side of TR-ES into our assessment, considering that heat vulnerability is unevenly distributed among urban residents, reflecting different TR-ES needs. By adopting the heat vulnerability assessment framework from the IPCC (2007), encompassing exposure, sensitivity, and adaptive capacity, we quantify heat vulnerability as a proxy for estimating TR-ES demand (Langemeyer et al., 2020; Mallen et al., 2019; Bradford et al., 2015).

Through spatially explicit assessments of TR-ES supply-demand mismatches, we aim to provide evidence-based information that can guide urban planning, addressing environmental inequities and identifying priority intervention areas for reducing heat-related vulnerabilities. This aligns with existing literature emphasizing the importance of such assessments in guiding effective urban interventions (Baró et al., 2015; Herreros-Cantis and McPhearson, 2021). We refer to TR-ES mismatch as the difference in either the quality or quantity between TR-ES supply and demand (Sebastiani et al., 2021; Geijzendorffer et al., 2015). We specifically aim to i) develop an integrated modelling approach that combines remote sensing, field data, and socio-demographic information to assess TR-ES supply and demand; ii) analyse the spatial distribution of the TR-ES supply-demand mismatches as a way to target priority intervention areas; iii) identify the sociodemographic and health factors that influence TR-ES supply–demand mismatches.

2. Methods

2.1. Study area

Our study focused on the mid-sized city of Vitoria-Gasteiz (Basque Country), located in the North of the Iberian Peninsula (Fig. 1) and internationally known by its ambitious urban greening policies, as reflected by the 2012 European Green Capital award. Vitoria-Gasteiz has numerous green and blue spaces designed as part of its publicly accessible UGI, including a 35 km-long green belt from the 1990s (Fig. 1). The city, with a population of 253,672 inhabitants (Instituto Nacional de Estadística (INE), 2022), experiences a temperate and humid climate. The average annual temperatures have ranged between 4.4 °C and 17.1 °C over the period from 1991 to 2021 (Errea et al., 2023). Surface UHI has been rising from approximately 5 °C in 2012 to 10.9 °C in 2022 (Olazabal et al., 2012; Errea et al., 2023). The natural value of some features within the green belt, notably the Salburua wetlands, the Zadorra River and Vitoria Mounts, were included in the Natura 2000 network and protected as community interest sites. In addition, the current local urban green infrastructure planning aims at the creation of nature-based solutions that also contribute to mitigating urban heat in strategically selected areas (Centro de Estudios Ambientales CEA, 2014).

2.2. Analytical framework

To address compatibility and transferability challenges in ES assessment models (Balbi et al., 2022), we adopted an integrated modelling approach based on FAIR (Findable, Accessible, Interoperable, and Reusable models and data) principles (Wilkinson et al., 2016). This involved combining the Artificial Intelligence for Environment & Sustainability (ARIES) modelling platform (Villa et al., 2014, 2017) with GIS tools to produce results that are accessible to urban planners. ARIES modelling was performed on k.LAB, an advanced modelling web-based software that connects spatial data and model components through semantics and machine reasoning (Marquez-Torres et al., 2023; Capriolo et al., 2020; Villa et al., 2014). ARIES, facilitated by k.LAB, automates ES and urban heat assessment through a modular approach, constructing models based on context-specific data (Villa et al., 2014). The AI engine in k.LAB optimizes workflows, enhancing the modelling process and aiding in the quantification of urban heat. All spatial data used for the assessment, including the workflow for various additions and geoprocesses to quantify urban heat and map ES dynamics, is loaded into k. LAB. This data is accessible for reuse, aligning with the FAIR principles. The incorporation of semantic technologies within k.LAB efficiently organizes and retrieves information. By hosting our models (i.e. heat exposure, ES supply and demand) data in the cloud, we improve the replicability and accessibility for both researchers and decision-makers. Notably, k.LAB's web-browser interface enables access to information, bridging the gap between research and practical application in urban planning.

Our integrated modelling approach was designed to comprehensively assess the spatial distribution of TR-ES supply and demand (Fig. 2). We used composite indicator that combines the ecological, biophysical and societal aspects of TR-ES supply and demand into a unitless, normalized value (Alam et al., 2016). To quantify the supply of urban TR-ES, we examined the ecological properties and functions of UGI (Fusaro et al., 2023; Sebastiani et al., 2021), including habitat quality as indicator of ecological integrity, and vegetation cover as a proxy for shading and evapotranspiration capacity. For assessing ES demand, we followed the IPCC AR5 framework (IPCC, 2014), which considers risk as the combination of urban heat hazard, exposure and associated vulnerability (Wang et al., 2023; Hsu et al., 2021). To assess these components of ES demand, we built a Heat Vulnerability Index (HVI), as a function of exposure, sensitivity and adaptive capacity, in order to account for vulnerability to urban heat hazard. Lastly, the assessment of TR-ES mismatches involved subtracting the supply from the demand at the census tract level. To operationalize this workflow (Fig. S1, Supp. Mat.), we developed different modules within the ARIES platform, along with an associated ontology and semantics. We also incorporated different data types to ARIES including environmental and socio-demographic data across different spatial scales.

2.3. Urban temperature regulation (TR-ES) supply

To quantify TR-ES supply we employed a composite indicator approach at the census tract level (Alam et al., 2016). We based our assessment on three indicators: i) the first indicator refers to the canopy cover, as the proportion of ground area covered by layers of leaves and woody vegetation when viewed from above (Locke et al., 2021), expressed as a percentage and used as a proxy for the vegetation shading effect. The indicator was estimated from PNOA LiDAR data (year 2017) at 1 m resolution (Instituto Geográfico Nacional, 2023) (Fig. S2, Supp. Mat.); ii) the second indicator is the mean Normalized Difference Vegetation Index (NDVI) and was obtained from Sentinel 2 images for the summer period of 2021–2022 at 10 m of spatial resolution. NDVI values above 0.25 were considered and validated by spatial overlay with orthophotos and urban land use maps (resolution of 10 m) (CEA, 2020). NDVI has been previously used as a proxy of TR-ES provision (Sebastiani et al., 2021; Marando et al., 2019); iii) the third indicator is based on a 10 m-resolution raster map of the spatial distribution of UGI habitat quality, derived from prior research conducted in Vitoria-Gasteiz (Aznarez et al., 2022) (Table S1, Supp. Mat). In this context, habitat quality is the ability of urban ecosystems to offer the necessary resources and conditions to support wildlife. Habitat quality is shaped by the proximity to and intensity of anthropic activities, resulting in a continuous spatial indicator that spans from 0 (low) to 1 (high). Higher habitat quality indicates higher productivity and ecological integrity, while lower habitat quality suggests habitat the influence of threats (e.g. fragmentation by roads and imperviousness) and edge effects, reducing the evapotranspiration and hence cooling potential of vegetation (Aznarez et al., 2022; Ewers and Banks-Leite, 2013). TR-ES supply for urban temperature regulation is calculated by Eq. (1) adapted from Sebastiani et al. (2021):

$$TRES = Cc + NDVI + HQ \quad (1)$$

where Cc represents the percentage of canopy cover by census tract, NDVI refers to the mean NDVI calculated for vegetation from 2022

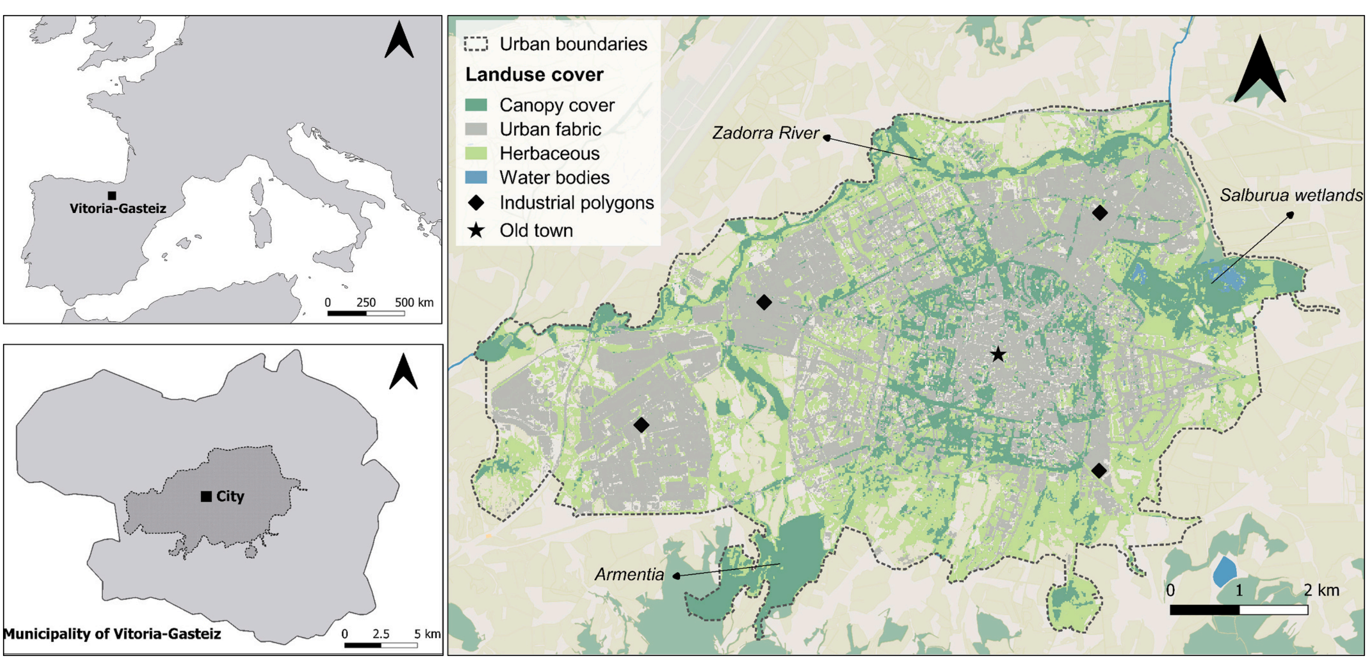


Fig. 1. Study area of Vitoria-Gasteiz with its location within the urban and municipal boundaries and main land covers, such as urban fabric, canopy cover, herbaceous cover, and water bodies. Black diamonds indicate industrial polygons and the black star indicates the historical city centre. Arrows indicate the major natural landmarks of the green belt.

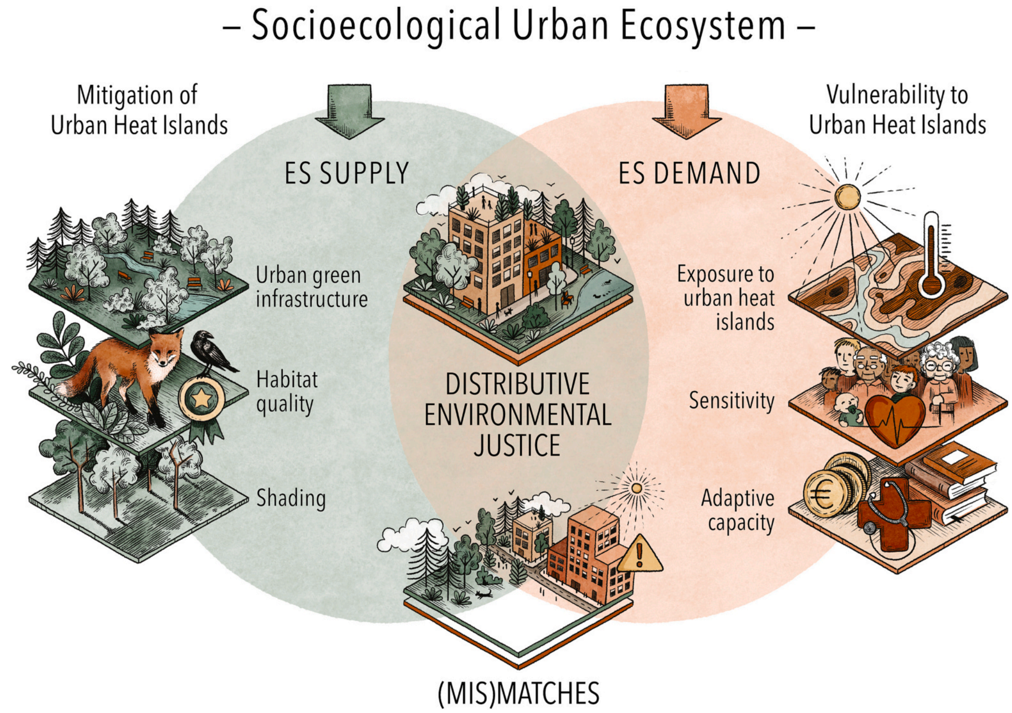


Fig. 2. Conceptual framework on urban temperature regulation ES (TR-ES) supply and demand, and their mismatches based on composite indicators. TR-ES supply is evaluated based on the ecological attributes of urban green infrastructure and TR-ES demand is based on urban heat vulnerability assessments. Spatial mismatches among TR-ES supply-demand underscores its significance for (distributive) environmental justice.

summer Landsat 8 imageries and HQ represents the mean habitat quality of UGI.

2.4. Urban temperature regulation (TR-ES) demand

The societal demand for urban temperature regulation was estimated based on the spatial distribution of the heat vulnerability index (HVI). To identify priority areas for heat-related risk reduction, we used a unitless characterization of social factors. We considered vulnerability to heat as a subtype of social vulnerability, defined by IPCC AR5 as the predisposition of social groups to adverse impacts including the sensitivity to harm and lack of capacity to adapt (Wisner, 2016). We built and calculated the HVI for Vitoria-Gasteiz for each census tract following Reid et al. (2009). To this, we summed up the exposure level (E_i) and sensitivity level (S_i) to heat and then we summed up indicators of reduced adaptive capacity while subtracting those associated with enhanced adaptive capacity level (A_i) as given in Eq. (2):

$$HVI = Ei + Si \mp Ai \tag{2}$$

For the development of the HVI specific to Vitoria-Gasteiz, we used spatial data on socio-economic and demographic variables at the census tract level, which was the finest resolution at which data was accessible and is generally the relevant spatial scale to urban planning and policies (Table S1, Supp. Mat.). Highlighting the importance of a finer spatial scale, our approach recognises the localised nature of urban green space usage. Residents predominantly experience urban green spaces in their immediate surroundings, aligning with the "distance decay" effect (Yok-Tan and Samsudin, 2017). This underscores the need for smaller scales in spatial studies, which is key for understanding dynamics that impact daily living experiences. Such an approach aligns with Maantay's (2002) recommendations for environmental health hazard assessments. Assessing hazards like heat at the census tract level, as opposed to aggregated city or county scales, enhances precision in identifying affected residents and comprehending the nuanced aspects of exposure within specific local contexts.

Heat exposure refers here to the urban population being exposed to high temperatures and related health impacts. This was assessed using LST (Fig. S4, Supp. Mat.) and population density as indicators (Wang et al., 2023). High-density urban areas with elevated temperatures are known to pose increased heat exposure risks (Manoli et al., 2019). The spatial distribution of exposure was mapped (Table S2, Supp. Mat.) by incorporating four overlapping spatial layers into our analysis: i) a raster map of population density to map the hotspots of anthropogenic heat, serving both as a measure for heat exposure and an aggravating factor for the UHI effect (Manoli et al., 2019; Jin et al., 2019); ii) NDVI to depict the density of vegetation, with areas with significantly low NDVI (<0.1) indicating bare soil, which contributes to LST intensity and therefore higher heat exposure (Marando et al., 2019; Tesfamariam et al., 2023); iii) LST to estimate the extent and magnitude of urban heat, as input for assessing the spatial distribution of heat hazards; and iv) land cover data to identify urban impervious surfaces.

To calculate sensitivity, we considered factors that could either amplify or mitigate the impact of heat exposure. These factors encompassed residents' age and health aspects (Mallen et al., 2019; Kuras et al., 2015; Reid et al., 2009). Our data included age-related metrics (percentage of the population aged $\leq$14 and $\geq$ 65) and health indicators, including respiratory diseases, diabetes and pulmonary conditions in both, male and female populations (see detailed information in Table S1, Supp. Mat.). For the health variables, we employed the Standardized Mortality Ratio (SMR), which measures the likelihood of higher-than-expected mortality rates within a specific group compared to a reference population. The SMR data were obtained from the Basque Mortality Atlas for the period 2013–2017, and the age-related metrics were sourced from the EUSTAT, the Basque Bureau of Statistics (2021).

Finally, to map heat-related adaptive capacity, we examined the capacities and resources accessible to city residents to cope with heat exposure. We identified education attainment, income, and foreign origin as potential factors influencing adaptive capacity to heat (Kuras et al., 2015; Reid et al., 2009). Specifically, above the median annual household gross income (€34,473) and high educational attainment (i.e.

residents with and above tertiary education) were assumed to be factors that can enhance adaptive capacity, potentially leading to reduced exposure to heat (Wang et al., 2023). Conversely, lower income and education attainment (i.e. residents with primary or no formal education), along with foreign origin (i.e. from Asia, Africa and America), were expected to indicate a lower adaptive capacity. The latter can be attributed due to difficulties in getting sufficient support from educational and healthcare institutions, as well as linguistic barriers for accessing knowledge and information (Keeler et al., 2019; Nayak et al., 2018). The lack of adaptive capacity was determined by summing factors indicating a lower adaptive capacity and subtracting those contributing to adaptive capacity. Consequently, higher values in this component indicate an increased lack of adaptive capacity to address heat-related challenges.

To allow for comparisons, we standardized the initial set of vulnerability-related variables to have an average of 0 and a standard deviation of 1. We then assessed the correlation between the selected variables by calculating pairwise Spearman's correlation coefficients (Fig. S3, Supplementary data) using the "ggally" package in R (Schloerke et al., 2021). Highly correlated variables were considered for elimination when deemed redundant to ensure a robust dataset. To simplify the interpretation and mitigate the influence of outliers, we categorized each variable into six distinct scores based on their standard deviations, i.e. z-score values (Table S3, Supp. Mat.). The specific scores were assigned to each category, ranging from 1 (i.e. minimal vulnerability) to 6 (i.e. highest vulnerability).

Drawing from Reid et al. (2009), and given the limited understanding of the individual impacts of each identified factor on vulnerability to urban heat, we assumed an equal weight and aggregated the assigned scores for each variable. This aggregation produced a cumulative HVI value for each census tract. To ensure that higher values align with increased vulnerability, the considered variables were adjusted. If a variable had a positive impact suggesting lower vulnerability, it was computed by subtracting it to contribute to the cumulative measure of increased vulnerability. To spatially represent the HVI values at the census tract level, these were normalized between 0 and 1 to also make them more easily comparable.

2.5. Spatial TR-ES supply-demand mismatch analysis

Each census tract was assigned TR-ES supply and demand values ranging from 0 (lowest) to 1 (highest). Supply indicated the normalized estimation of TR-ES attributed to UGI, while demand reflected the societal need for exposure reduction and the calculated HVI. To map TR-ES supply-demand mismatches, we adopted a pragmatic approach involving the subtraction of the supply from the demand index to estimate a TR-ES budget for each census tract (following Burkhard et al., 2012; Herreros-Cantis and McPhearson, 2021). The resulting values spanned from 1 to −1, with a value of 1 representing the highest potential for mismatch, indicating high TR-ES demand in the face of low supply. Lower values indicated areas where the supply of TR-ES exceeded potential demand, with values near 0 suggesting a balance between potential demand and supply. To identify the patterns driving supply–demand mismatches, we used the Getis-Ord Gi* hotspot analysis within ArcMap 10.7.1 (ESRI). This analysis consists in grouping census tracts into (seven) clusters based on their z-scores and *p*-values where high or low values exhibited spatial clustering based on their initial supply-demand mismatch value. These clusters represent cold (very low values) and hot (very high values) spots with specific confidence intervals (90 %, 95 %, and 99 %), and non-significantly clustered mismatch.

To discern the individual influences of the selected variables comprising the HVI index and identify the key socio-demographic and health variables influencing the spatial mismatches in TR-ES, we used generalized linear models (GLMs). GLMs, an extension of classical linear models, accommodate a broader range of response variables with non-normal distributions and non-constant variance. To associate the mismatch values with the combination of these variables, we used a stepwise regression approach (Table S1, Fig.S7, Supp. Mat.). Stepwise regression systematically adds or removes predictors based on statistical criteria (here we used Akaike Criterion) to identify the most influential variables in the model. We iteratively refined the model by considering the contribution of each variable until achieving the best-fitting and parsimonious model. We then checked the model assumptions by visual inspection of the residual plots. To describe how socio-demographic and health-related variables were associated with the generated clusters (cold and hot spots), we applied a principal component analysis (PCA). The PCA allowed us to discern patterns and relationships among variables, providing an initial understanding of the data structure. We then identified the contribution and significance of each variable that differentiated the cold and hot clusters performing a similarity percentage analysis (SIMPER). These analyses were conducted using R, version 1.4.1717 (R Core Team 2022), with specific packages dedicated to: 'vegan' for multivariate statistics, 'tidyverse' for data handling, 'sjPlot' for representation, and 'performance' for model validation.

3. Results

3.1. Spatial patterns of urban exposure to heat hazard

To analyse heat spatial distribution, we mapped summer LST. Temperature ranged between 24.93 and 55.80 °C (Fig. S4, Supp. Mat). The zones with higher temperatures were primarily observed in industrial areas that are characterized by heat-absorbing materials and sparse vegetation cover. The heat exposure map (see Fig. S5, Supp. Mat.), shows moderate to high values (ranging from 0.4 to 1) in areas surrounding the city centre, including industrial and residential areas. These areas correspond to higher urban densities, compactness and LST. Heat exposure values decreased towards periurban areas.

3.2. Spatial patterns of urban temperature regulation (TR-ES) supply and demand

Fig. 3 shows the spatial distribution of (a) TR-ES supply and (b) TR-ES demand in Vitoria-Gasteiz at the census tract level. Higher TR-ES supply values (0.6 to 1) were predominantly found within and around large urban parks, forests, wetlands and foothills in the green belt, which constituted 12.04 % of the census tracts. The green belt is characterized by land uses such as forests, wetlands, and foothills extending towards the periurban border. Lower TR-ES supply values (ranging from 0 to 0.2) were primarily focused in the urban core and industrial zones. These zones (Fig. 1), often featured industrial polygons and older developments with sparse vegetation cover and higher impervious surface densities.

Regarding ES demand, 65 out of 166 census tracts (39.16 %), displayed either high (55 census tracts) or very high (10 census tracts) levels of vulnerability to heat. The old town of Vitoria-Gasteiz (see Fig. 1), central areas and the recently developed periurban areas, exhibited relatively higher heat vulnerability (Fig. S6d, Supp. Mat). As a result, residents living in these areas face increased heat exposure (Fig. S5, supp. Mat), contributing to a greater demand for TR-ES.

3.3. Spatial patterns of TR-ES mismatches

The average general TR-ES supply–demand mismatch index was 0.21, with positive values (i.e. supply < demand) prevalent in 75 % of the census tracts (Fig. 4a). The highest mismatch values (0.4 to 1), were observed in the city centre, industrial zones, and recent urban developments. Conversely, areas with the lowest mismatch values (−0.4 to −1) were primarily found in residential census tracts located around the green belt and to the Southern part of the city.

Hotspot analysis of TR-ES mismatches values (Fig. 4b), showed

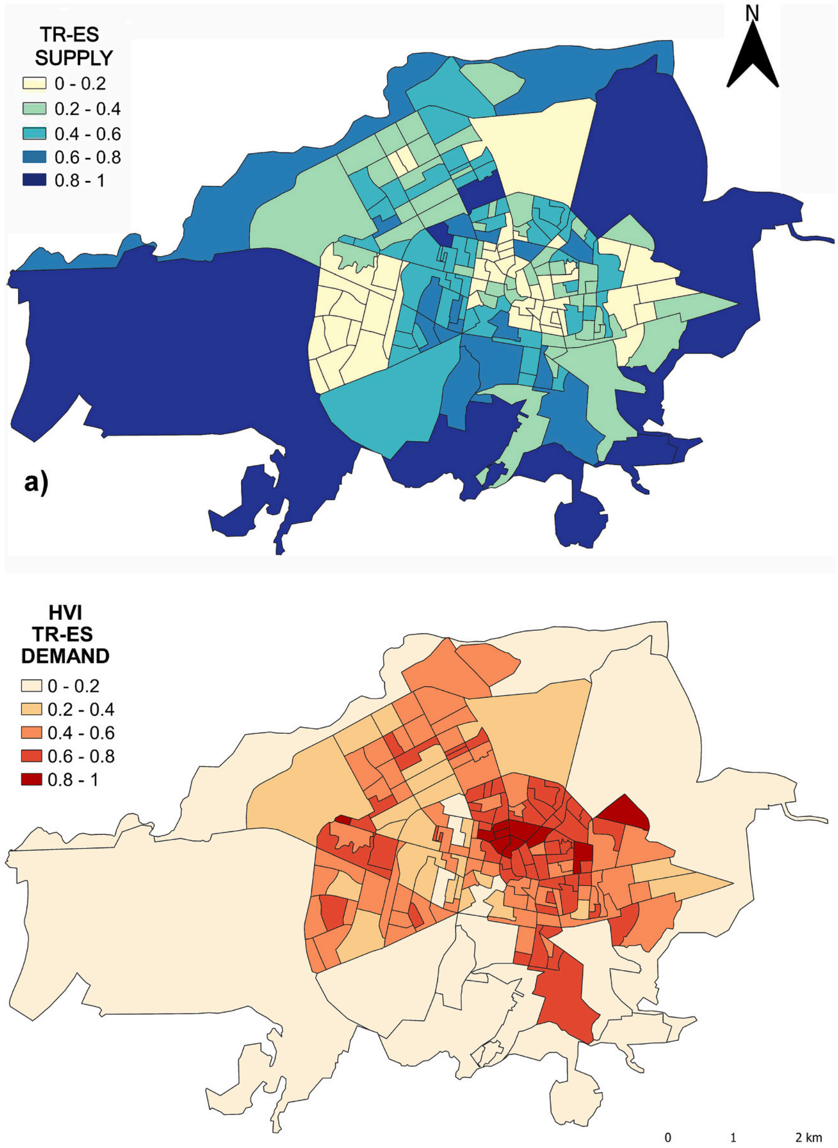


Fig. 3. Spatial distribution of urban temperature regulation (TR-ES) supply and vulnerability to heat index (as demand) indicators at the census tract level. Interpretation values refer to Very low (0–0.2), Low (0.2–0.4), Moderate (0.4–0.6), High (0.6–0.8) and Very high (0.8–1).

clustering patterns based on their z-scores. The top 10 % of z-scores (hot spots) accounted for 39.76 % of the census tracts, which suggest unsatisfied demand for TR-ES in these areas, as also shown in the HVI (Fig. 3). Hot spots were associated with a higher average exposure (0.74) and a lower (than the median) household income (avg.: €32,663) compared to cold spots (Table S4, Supp. Mat). They also had a higher proportion of individuals with low educational attainment (40.68 %) and born in the American continent (9.22 %). Conversely, the lowest 10 % confidence interval supply–demand balance z-score values (cold spots) covered 18.07 % of the census tracts, suggesting satisfied demand for TR-ES. Cold spots showed considerably lower median heat exposure (0.54) and higher (than median) household income (avg.: €44,918). Furthermore, 42.17 % of census tracts displayed no significant spatial clustering.

TR-ES mismatches were associated in 76.3 % of the variance, negatively with household income and positively with SMR of lung cancer in men, population below the age of 14, population born in America, and exposure to heat (Table 1). Household income had a low but significant negative effect on the TR-ES mismatch, while the other health and demographic variables showed positive and statistically significant effects, although relatively small, except for heat exposure, which had a medium effect (Fig. S7, Supp. Mat.).

The PCA accounted for 53 % of the total variance on its first two components and showed a differentiated association of cold spot from hot spot clusters regarding the socio-environmental and health variables (Fig. 5, Table S5, Supp. Mat.). Cold spot clusters were positively associated with income, high education attainment, and female SMR for respiratory diseases (these variables were negatively associated with hot clusters). Contrastingly, hot clusters were positively associated with heat exposure, elderly population, foreign origin, low education attainment, and male and female SMR for diabetes and lung cancer.

Complementing PCA, which facilitated dimensionality reduction and the identification of overarching patterns in our data structure, SIMPER offered a detailed examination of individual variables, quantifying their contribution and significance in distinguishing between hot and cold spots. The SIMPER analysis identified that the main variables associated with the difference between hot and cold spots were higher heat exposure, lower education attainment, SMR of respiratory diseases in men, SMR of lung cancer in women, and residents of American origin in hot spot clusters. In contrast, cold spots were mainly characterized by higher

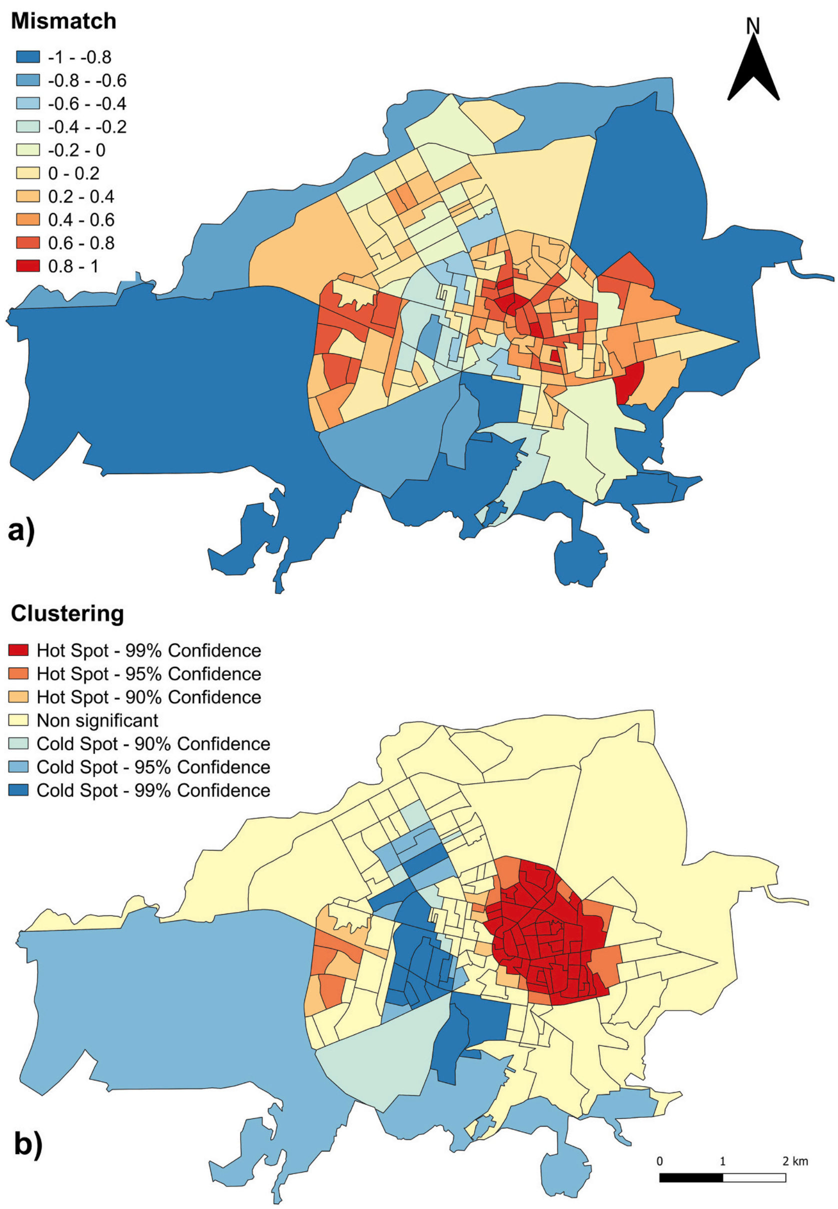


Fig. 4. Spatial distribution of a) Accumulated supply-demand mismatch values at the census tract level, ranging from −1 (supply > demand) to 1 (supply < demand), with values closer to 0 indicating balance (supply = demand). b) Spatial clustering analysis (Getis Ord Gi*) of supply-demand mismatch values at the census tract level. Clusters are categorized based on z-scores and *p*-values ($p > 0.05$) from the cluster analysis. Coldspots (supply > demand) are represented in shades of blue, while hotspots (supply < demand) are depicted in shades of red and orange at 90 %, 95 %, and 99 % confidence intervals. Census tracts in yellow indicate no significant spatial clustering.

Table 1
GLM model outputs for the effects of heat exposure, population below the age of 14, SMR of lung cancer in men, population born in America, and household income on model-estimated ES supply-demand mismatch values in Vitoria-Gasteiz.

Mismatch = Income + M_lung_cancer + ≤14 age + American + Heat exposure

	Estimates	*std. Error*	*CI*	*F*	*p*
(Intercept)	0.21	0.01	0.18–0.24	14.52	<2e-16
Income	−0.12	0.02	−0.15 to −0.08	−6.53	8.21e-10
M_lung_cancer	0.08	0.02	0.05–0.11	4.88	2.60e-06
≤ 14 age	0.13	0.02	0.10–0.17	7.90	4.31e-13
American	0.08	0.02	0.04–0.11	4.01	9.27e-05
Heat exposure	0.21	0.02	0.17–0.24	12.20	<2e-16
Observations	166				
R^2 adjusted	0.763				

income, high education attainment, and SMR of respiratory diseases in women (Table 2).

4. Discussion

4.1. Novel contributions in the assessment of TR-ES supply and demand

Central areas, like the medieval quarter, and residential census tracts near industrial sites (Fig. 3), exhibit high values of heat vulnerability marked by increased heat hazard (Fig. S4, Supp. Mat.) and low values of TR-ES supply, suggesting unsatisfied demand for this ES. These areas are characterized by heat-absorbing materials, compact structures, high population density and sparse vegetation. These characteristics exacerbate local temperatures, leading to UHI effects and TR-ES mismatches. These mismatches also result from the city's exposure to heat and the limited capacity to increase TR-ES supply, thereby increasing heat-

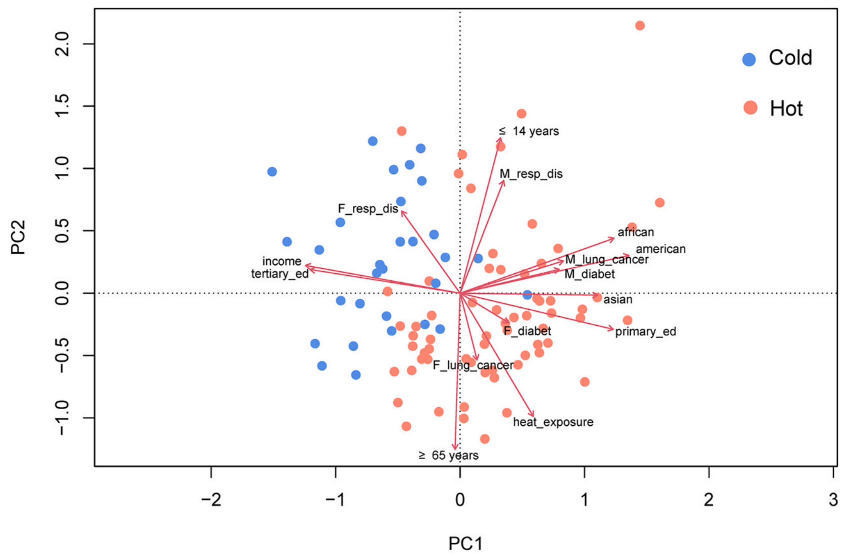


Fig. 5. Principal Component Analysis (PCA) ordination biplot for hot (red dots) and cold spots (blue dots) clustering units and socio-economic and health variables used as indicators of heat vulnerability. Abbreviations: Tertiary education (tertiary_ed), respiratory disease in women (F_resp_dis), children (≤ 14 years), elderly (≥ 65 years), diabetes in women (F_diabet), respiratory disease in men (M_resp_dis), diabetes in men (M_diabet), primary education (primary_ed), lung cancer in men (M_lung_cancer), lung cancer in women (F_lung_cancer). The first two axes components (axes) accounted for 53 % of the variance (Axis 1: 32.5 %, Axis 2: 20 %).

Table 2
SIMPER analysis results for variables that contributed to the dissimilarity between a) HOT spots and b) COLD spots clustering patterns. Bold variables are significant and organised by relative contribution.

Variable	Dissimilarity (%)	SD	Contribution (%)	p	Ratio	Abundance
Heat exposure	2.58	2.36	14.50	**0.001**	1.089	HOT > COLD
M_lung_cancer	1.96	1.49	25.50	0.189	1.315	HOT > COLD
Income	1.54	1.49	34.10	**0.001**	1.033	HOT < COLD
Tertiary_ed	1.46	1.02	42.30	**0.001**	1.436	HOT < COLD
F_resp_dis	1.45	1.18	50.40	**0.013**	1.221	HOT < COLD
Primary_ed	1.43	0.92	58.50	**0.001**	1.553	HOT > COLD
≥ 65 years	1.42	1.00	66.50	0.127	1.419	HOT > COLD
M_resp_dis	1.30	0.97	73.80	**0.010**	1.340	HOT > COLD
F_lung_cancer	1.24	0.93	80.70	**0.010**	1.325	HOT > COLD
F_diabet	0.87	0.68	85.60	0.067	1.283	HOT > COLD
M_diabet	0.82	0.66	90.20	0.246	1.235	HOT > COLD
American	0.56	0.44	93.40	**0.005**	1.275	HOT > COLD
≤ 14 years	0.55	0.56	96.50	0.557	0.9741	HOT > COLD
African	0.50	0.54	99.30	0.375	0.9324	HOT > COLD
Asian	0.13	0.12	100	0.179	1.0481	HOT < COLD

related vulnerability among residents. Our findings align with previous research in Vitoria-Gasteiz that has identified central and industrial areas as the most unfavourable, characterized by elevated temperatures and insufficient UGI, making them particularly prone to urban heat impacts (Olazabal et al., 2012; Rodríguez-Gómez et al., 2022; Errea et al., 2023).

Our study introduces a novel approach by integrating heat vulnerability indicators into TR-ES demand assessments (Fig. 2), highlighting the multifaceted nature of ES demand often overlooked when assessments rely solely on population distribution (Baker et al., 2021; Wolff et al., 2015). The HVI index (Fig. 3 and Fig. S6, Supp. Mat.) highlights the importance of identifying heat-vulnerable communities, emphasizing the need for tailored interventions that integrate both public health and greening initiatives (Langemeyer et al., 2020; Nayak et al., 2018; Reid et al., 2009). This approach is a valuable tool for priority-setting of UGI projects and promoting equity within urban management plans.

We have also mapped urban TR-ES supply, based on UGI quantity, quality and its ecological functions (Park et al., 2017; Yang and Wang, 2017). By using ecological indicators like habitat quality, canopy cover and NDVI, we have expanded upon traditional assessments of UGI capacity to provide cooling effects solely based on vegetation indexes while providing comprehensive, easily adaptable and replicable estimators (Aznarez et al., 2022; Wang et al., 2023). This approach aligns with recent research indicating that factors like ecological integrity and connectivity significantly influence the temperature regulation supply of urban ecosystems (Luo and Fu, 2023). Moreover, prior studies emphasize that vegetation cover, patch size, species composition, and diversity are key drivers of microclimate temperature regulation (Kraemer and Kabisch, 2022; Gillerot et al., 2022; Zhang et al., 2022). Integrating the habitat quality indicator into TR-ES supply mapping complements widely-used proxies like canopy cover and NDVI. A higher habitat quality indicates relatively higher productivity and ecological integrity, whereas a lower habitat quality indicates higher exposure to anthropogenic threats such as mechanised access and urban densification. These threats contribute to habitat fragmentation and the resulting influence of edge effects, reducing the evapotranspiration and hence cooling potential of vegetation. Consequently, vegetation patches exposed to external microclimatic conditions can limit forests capacity to supply TR-ES (Ewers and Banks-Leite, 2013).

We have found that areas with extensive and less fragmented green spaces, such as the green belt and large urban parks (Fig. 3), are associated with higher levels of TR-ES supply. In contrast, industrial and central areas, which have limited TR-ES supply exhibit higher ecological fragmentation (Aznarez et al., 2022). This emphasizes the relevance of considering land-use patterns, particularly fragmentation, when examining TR-ES dynamics in urban landscapes. Understanding how compact and extensive urbanization models influence ES offer valuable insights for optimizing urban land management for effective TR-ES provision (Stott et al., 2015). Our study highlights the role of ecological integrity and fragmentation in shaping temperature regulation ES in urban areas.

4.2. Implications of TR-ES mismatches for urban environmental justice

Our analysis of TR-ES supply-demand mismatches (Fig. 4) has revealed significant urban climate inequalities shaped by socio-demographic factors, including health aspects, reflecting various vulnerability dimensions. TR-ES mismatches are primarily associated with variables related to health condition, age, foreign origin, and increased heat exposure, leading to higher unsatisfied demand for TR-ES in areas with these characteristics (Table 1, Fig. S7, Supp. Mat.). This finding aligns with previous research indicating that vulnerable groups, such as the elderly, children, migrants, people with chronic diseases, and those with limited exposure to UGI face elevated health risks from extreme heat (e.g. Amorim-Maia et al., 2023; Keeler et al., 2019; Nayak et al., 2018; Bradford et al., 2015; Reid et al., 2009). Notably, high-income neighbourhoods in Vitoria-Gasteiz, characterized by higher vegetation cover and lower population density, exhibit lower TR-ES mismatch values.

Spatially clustering of TR-ES mismatch values into hot spot and cold spot areas can (Figs. 4b and 5) provide valuable information for priority-setting and designing of UGI interventions addressing the unique needs of these areas. Hot spots in Vitoria-Gasteiz, associated with socioeconomically disadvantaged areas with higher heat vulnerability, contrast with cold spots primarily found in more affluent areas (Table 2; Table S4. Supp. Mat.). This finding aligns with prior research highlighting the uneven distribution of canopy cover in cities, which is influenced by socioeconomic factors, ultimately contributing to the stratification of environmental stressors, such as the UHI effect (Chakraborty et al., 2019; Jenerette et al., 2011). These disparities hinder equitable access to regulating ES, as shown by luxury effects related to canopy cover (Schell et al., 2020; Jenerette et al., 2013). Higher-income areas benefit from reduced urban heat vulnerability and better TR-ES supply, while lower-income areas being more exposed to heat and rely more on public resources to cope with it (Jenerette et al., 2011).

Our findings also highlight the heat risks for residents in hot spots, especially in areas with high LST (i.e. heat hazard), limited vegetation, and high population density (Figs. S4 and S5, Supp. Mat.). We thus emphasize the need to explicitly integrate environmental and climate justice principles into UGI development plans to address distributional environmental injustices and mitigate heat-related risks by those who are more vulnerable. The uneven distribution of UGI contributing to TR-ES mismatches in Vitoria-Gasteiz also aligns with prior research on environmental injustices and increased climate vulnerability (Herreros-Cantis and McPhearson, 2021). This finding complements prior research in Vitoria-Gasteiz that suggests that management and land use legacies are key factors in shaping the distribution of UGI-based regulating ES, as is the case of older areas with well-established canopy (Aznarez et al., 2023). However, the socioeconomic status also influences UGI accessibility, quality, and quantity (Schell et al., 2020). Our results further indicate that the majority of residents Vitoria-Gasteiz (75 % of census tracts), lack access to UGI that can supply TR-ES, in contrast to those living in higher-income areas. This observation holds significance, especially considering the extensive city-wide green space coverage, where 31 % census tracts in the city have over 30 % canopy cover (Fig. S2, Supp. Mat.).

4.3. Considerations for urban planning and policy

Addressing the challenges posed by the rising temperatures in urban landscapes requires strategic interventions. Areas with the highest heat exposure, such as the central and nearby industrial areas in Vitoria-Gasteiz (Fig. S5, Supp. Mat.), offer opportunities for long-term interventions. These may involve extensive tree planting, enhancing canopy cover, and allowing vegetation to mature (Aznarez et al., 2023). In locations where greening measures may not be feasible, the use of heat-reflective materials could be considered (Mallen et al., 2019).

However, areas characterized by high vulnerability to heat, particularly those with inequalities in access to TR-ES (Fig. 4), require establishing adaptation strategies that address multifaceted and intersecting factors associated with increased demand for TR-ES (Table 1; Fig. 5). Potential approaches would include greening initiatives designed to enhance TR-ES supply and the establishment of climate shelters. These shelters can be outdoor settings integrated within UGI, providing shade and canopy cover, or indoor facilities offering refuge and assistance during extreme heat events. Both approaches aim to minimize outdoor exposure through favourable environmental conditions and access to drinking water, particularly for vulnerable groups like the elderly (Amorim-Maia et al., 2023; Keeler et al., 2019; Bradford et al., 2015). Effective implementation of these measures relies on understanding the spatial variability of heat-related vulnerability, as highlighted by our TR-ES mismatch mapping approach (Fig. 4). Therefore, enhancing adaptive capacities within urban landscapes goes beyond increasing overall green cover; it involves targeted efforts that address specific population needs, community-based resilience actions, awareness-raising, and measures beyond green spaces expansion.

Increasing urban vegetation mitigates UHI effects and reduces local temperatures (Marando et al., 2019, 2022). However, compact cities like Vitoria-Gasteiz must balance effective urban development with UGI preservation and expansion. Urban densification, while resource-efficient, may hinder TR-ES provision (Mascarenhas et al., 2019; Sebastiani et al., 2021; Aznarez et al., 2023). Given the limited space for expanding greenery, an integrated approach that combines grey-green infrastructure is key (Langemeyer et al., 2020). While recognizing that UGI benefits are not linearly correlated with vegetation quantity (Whitlow et al., 2014), enhancing canopy coverage can help achieve a better TR-ES supply-demand balance. Optimizing UGI spatial distribution through green roofs, green walls, pocket parks, and larger green spaces where feasible, all interconnected for efficient resource use, is seen as crucial. Diversifying vegetation structure within existing UGI, beyond traditional lawns, can also offer a cost-effective approach for addressing urban heat hazards, especially in areas where tree planting is not feasible due to physical constraints or management considerations (Francoeur et al., 2021). This approach can help balance TR-ES supply and demand while also providing habitat for biodiversity, with synergies with other urban ES like pollination and storm water mitigation (Francoeur et al., 2021; Kremer et al., 2016).

UGI should be biodiverse and multifunctional, considering tree species that are resilient to climate change (Lanza and Stone Jr, 2016). While deciduous tree species are effective for urban heat mitigation due to their shading and evapotranspiration (Sebastiani et al., 2021), a sole focus on increasing TR-ES supply may pose risks, including increased vulnerability to climate change-related impacts like pests and diseases. Evaluating tree-planting schemes for their impact on urban biodiversity and ecological functions and services is crucial, emphasizing the importance of maintaining a diverse plant species range for supporting biodiversity. Successful implementation of these strategies, especially in socially vulnerable areas, requires collaborative efforts, legislative support, and community involvement. Recognizing that UGI design and management are also influenced by cultural and aesthetic aspects, these factors should be considered in urban planning (Francoeur et al., 2021; Grove et al., 2014).

4.4. Limitations and future research

Our study has various limitations. The reliance on relative values for TR-ES (supply, demand, and mismatches) (Figs. 3 and 4), may limit applicability and comparability across other cities and locations. The use of standardized indicators for TR-ES supply and demand, lacking a common framework may introduce subjectivity (Sebastiani et al., 2021), which is also related to the incommensurability of considered variables. Partially addressing this incommensurability, we used unitless composite indicators which integrates multiple dimensions of different variables (Alam et al., 2016). The decision to assign equal weights in our HVI index simplified the modelling process but potentially overlooked variation in the actual contributions of the individual variables. To address this, GLM and PCA helped discern the individual influences of variables, enhancing the understanding of their roles in TR-ES mismatches. Additionally, our analysis of TR-ES demand does not consider residents' preferences and values, which can significantly affect their subjective vulnerability to heat. For instance, individuals prioritizing air conditioning or engaging less with urban green spaces may experience higher heat risks. Integrating these insights into the analysis is essential for targeted interventions. However, collecting representative data on people's preferences and values can be time-consuming and resource-intensive. Integrating the HVI index in TR-ES demand quantification, may offer a cost-effective way to account for intersecting factors shaping resident's needs, improving current methods.

Additionally, advancing our understanding of urban TR-ES mismatches can benefit from incorporating multi-temporal data, including seasonal variations in LST or NDVI indicators and addressing spatial and temporal variability (Yao et al., 2021). Satellite-derived LST is a practical way for mapping ambient temperature indicators (Fig. S4, Supp. Mat.), but it also has limitations. Future research may benefit from integrating air temperature data from urban weather monitoring stations, closely associated with human perceptions of heat, comfort, and health (Wang et al., 2023; Chakraborty et al., 2019). In our case, remote sensing seems suitable for capturing the spatial heterogeneity of urban climate variability. Our combination of satellite-derived LST with NDVI and population density yielded consistent results (Figs. 3, S4 and S5, Supp. Mat.), aligning with previous research in the study area (Rodríguez-Gómez et al., 2022).

It should also be noted that equal weighting of TR-ES demand indicators may overlook variations in their contribution to heat vulnerability, requiring further refinement to consider the distinct impacts of each individual indicator (Wang et al., 2023). Data limitations led to the exclusion of factors like access to air conditioning, and living alone, which can exacerbate vulnerability, particularly among socially isolated elderly individuals who may not recognize heat-related symptoms or seek help (Bradford et al., 2015). Addressing heat-related vulnerabilities from a distributive justice perspective requires examining the multifaceted barriers faced by the most heat-vulnerable groups, including inadequate housing, limited access to urban cooling, and socioeconomic inequalities (Amorim-Maia et al., 2023). We thus emphasize the need for further research to address urban heat risks and the interplay between socioeconomic and biophysical factors in vulnerability assessments, calling for exploration and resolution of methodological and data-related challenges.

5. Conclusions

Exposure to urban heat poses a pressing challenge in the face of climate crisis, with uneven health and environmental impacts in cities. UGI can play a key role in mitigating these impacts by reducing ambient temperatures. Our study offers valuable insights into the complex relationships among urban heat, the spatial distribution of TR-ES, and heat vulnerability in urban areas. Through a comprehensive assessment of TR-ES mismatches in the Vitoria-Gasteiz case, combining remote sensing, field data, and socio-demographic data we have identified key priorities for UGI planning at the intersection of environmental justice and climate adaptation.

To plan effective urban heat mitigation interventions, it is crucial to understand the social and health determinants contributing to unequal heat risks. Our research contributes a replicable workflow and modelling approach that serves as a monitoring and spatial prioritization tool. We have identified the locations of vulnerable communities affected by heat hazards, enabling evidence-based recommendations tailored to specific needs for mitigating heat-related vulnerabilities. Addressing these challenges is key to ensuring the well-being of urban residents as cities confront growing climate impacts. Integrating vulnerability considerations and ES distribution analyses into practical urban planning and management strategies is crucial. This represents not only a shift towards urban sustainable and green transitions, but more importantly, towards just and green transitions. By optimizing UGI and addressing local community needs, urban adaptation plans can work towards mitigating urban heat while promoting equity and creating sustainable urban environments.

CRediT authorship contribution statement

Celina Aznarez: Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sudeshna Kumar:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Alba Marquez-Torres:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Unai Pascual:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Francesc Baró:** Writing – review & editing, Supervision, Resources, Methodology, 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

Data will be made available on request.

Acknowledgements

CA was supported by the Doctoral INPhINIT–INCOMING program, fellowship code (LCF/BQ/DI20/11780004), from “la Caixa” Foundation (ID 100010434). This research is supported by María de Maeztu Excellence Unit 2023-2027 Ref. CEX2021-001201-M, funded by MCIN/AEI/10.13039/501100011033. This research contributes to the ICTA-UAB “María de Maeztu” Programme for Units of Excellence of the Spanish Ministry of Science and Innovation (CEX2019-000940-M).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171215.

References

Alam, M., Dupras, J., Messier, C., 2016. A framework towards a composite indicator for urban ecosystem services. Ecol. Indic. 60, 38–44. https://doi.org/10.1016/j.ecolind.2015.05.035.

Amorim-Maia, A.T., Anguelovski, I., Connolly, J., Chu, E., 2023. Seeking refuge? The potential of urban climate shelters to address intersecting vulnerabilities. Landsc. Urban Plan. 238, 104836 https://doi.org/10.1016/j.landurbplan.2023.104836.

Aznarez, C., Svenning, J.-C., Taveira, G., Baró, F., Pascual, U., 2022. Wildness and habitat quality drive spatial patterns of urban biodiversity. Landsc. Urban Plan. 228 (April), 104570 https://doi.org/10.1016/j.landurbplan.2022.104570.
Aznarez, C., Svenning, J., Pacheco, J.P., 2023. Luxury and legacy effects on urban biodiversity , vegetation cover and ecosystem services. Npj Urban Sustain. 3 (47) https://doi.org/10.1038/s42949-023-00128-7.
Baker, F., Smith, G.R., Marsden, S.J., Cavan, G., 2021. Mapping regulating ecosystem service deprivation in urban areas: a transferable high-spatial resolution uncertainty aware approach. Ecol. Indic. 121, 107058 https://doi.org/10.1016/j.ecolind.2020.107058.
Balbi, S., Bagstad, K.J., Magrach, A., Sanz, M.J., Aguilar-Amuchastegui, N., Giupponi, C., Villa, F., 2022. The global environmental agenda urgently needs a semantic web of knowledge. Environ. Evid. 11 (1), 1–6. https://doi.org/10.1186/s13750-022-00258-y.
Ballester, J., Quijal-zamorano, M., Fernando, R., Turrubiates, M., Pegenaute, F., Herrmann, F.R., Robine, J.M., Basagaña, X., 2023. *H*eat-related mortality in Europe during the summer of 2022. Nat. Med. 29 https://doi.org/10.1038/s41591-023-02419-z.
Baró, F., Haase, D., Gómez-Baggethun, E., Frantzeskaki, N., 2015. Mismatches between ecosystem services supply and demand in urban areas: a quantitative assessment in five European cities. Ecol. Indic. 55, 146–158. https://doi.org/10.1016/j.ecolind.2015.03.013.
Baró, F., Calderón-Argelich, A., Langemeyer, J., Connolly, J.J.T., 2019. Under one canopy? Assessing the distributional environmental justice implications of street tree benefits in Barcelona. Environ. Sci. Pol. 102, 54–64. https://doi.org/10.1016/j.envsci.2019.08.016.
Bradford, K., Abrahams, L., Hegglin, M., Klima, K., 2015. A heat vulnerability index and adaptation solutions for Pittsburgh, Pennsylvania. Environ. Sci. Technol. 49 (19), 11303–11311. https://doi.org/10.1021/acs.est.5b03127.
Burkhard, B., Maes, J., 2017. Mapping Ecosystem Services, 1. Advanced Books e12837.
Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012. Mapping ecosystem service supply, demand and budgets. Ecol. Indic. 21, 17–29. https://doi.org/10.1016/j.ecolind.2011.06.019.
Capriolo, A., Boschetto, R.G., Mascolo, R.A., Balbi, S., Villa, F., 2020. Biophysical and economic assessment of four ecosystem services for natural capital accounting in Italy. Ecosyst. Serv. 46, 101207 https://doi.org/10.1016/j.ecoser.2020.101207.
Centro de Estudios Ambientales (CEA), 2020. Land Use Cover Maps for Vitoria-Gasteiz. Retrieved from: https://www.vitoria-gasteiz.org/wb021/was/contenidoAction.do?idioma=es&uid=app_j34_0074.
Centro de Estudios Ambientales CEA, 2014. The Urban Green Infrastructure of Vitoria-Gasteiz: A Proposal Document.
Chakraborty, T., Hsu, A., Manya, D., Sheriff, G., 2019. Disproportionately higher exposure to urban heat in lower-income neighborhoods: a multi-city perspective. Environ. Res. Lett. 14 (10) https://doi.org/10.1088/1748-9326/ab3b99.
Chen, K., Boomsma, J., Holmes, H.A., 2023. A multiscale analysis of heatwaves and urban heat islands in the western U.S. during the summer of 2021. Sci. Rep. 13, 9570. https://doi.org/10.1038/s41598-023-35621-7.
Clarke, L.W., Jenerette, G.D., Davila, A., 2013. The luxury of vegetation and the legacy of tree biodiversity in Los Angeles, CA. Landsc. Urban Plan. 116, 48–59.
Cowan, T., Purich, A., Perkins, S., Pezza, A., Boschat, G., Sadler, K., 2014. More frequent, longer, and hotter heat waves for Australia in the twenty-first century. J. Clim. 27 (15), 5851–5871. https://doi.org/10.1175/JCLI-D-14-00092.1.
Dworczyk, C., & Burkhard, B. (2021). Conceptualising the demand for ecosystem services–an adapted spatial-structural approach. One Ecosyst. Ecol. Sustain. Data J. 6 (2021), 6, e65966. *doi:*https://doi.org/10.3897/oneeco.6.e65966.
Errea, C.L., de Almeida, C.R., Gonçalves, A., Teodoro, A.C., 2023. Remote sensing analysis of the surface urban heat island effect in Vitoria-Gasteiz, 1985 to 2021. Remote Sens. 15 (12), 3110. https://doi.org/10.3390/rs15123110.
Eustat. Basque Statistics Office. Municipal Statistics for Inhabitants. https://https://www.eustat.eus/estadisticas/tema_25/opt_1/tipo_1/ti_censos-de-poblacion-y-viviendas/temas.html (2021) (accessed 23th February 2023).
Ewers, R.M., Banks-Leite, C., 2013. Fragmentation impairs the microclimate buffering effect of tropical forests. PLoS One 8 (3), e58093.
Fischer, E.M., Schär, C., 2010. Consistent geographical patterns of changes in high-impact European heatwaves. Nat. Geosci. 3 (6), 398–403. https://doi.org/10.1038/ngeo866.
Francoeur, X.W., Dagenais, D., Paquette, A., Messier, C., 2021. Complexifying the urban lawn improves heat mitigation and arthropod biodiversity. Urban For. Urban Green. 60 https://doi.org/10.1016/j.ufug.2021.127007.
Fusaro, L., Nardella, L., Manes, F., Sebastiani, A., Fares, S., 2023. Supply and demand mismatch analysis to improve regulating ecosystem services in Mediterranean urban areas: insights from four Italian municipalities. Ecol. Indic. 155, 110928 https://doi.org/10.1016/j.ecolind.2023.110928.
Geijzendorffer, I.R., Martín-López, B., Roche, P.K., 2015. Improving the identification of mismatches in ecosystem services assessments. Ecol. Indic. 52, 320–331. https://doi.org/10.1016/j.ecolind.2014.12.016.
Gillerot, L., Landuyt, D., Oh, R., Chow, W., Haluza, D., Ponette, Q., Verheyen, K., 2022. Forest structure and composition alleviate human thermal stress. Glob. Chang. Biol. 28 (24), 7340–7352. https://doi.org/10.1111/gcb.16419.
González-García, A., Palomo, I., González, J.A., López, C.A., Montes, C., 2020. Quantifying spatial supply-demand mismatches in ecosystem services provides insights for land-use planning. Land Use Policy 94, 104493. https://doi.org/10.1016/j.landusepol.2020.104493.
Grimm, N.B., Foster, D., Groffman, P., Grove, J.M., Hopkinson, C.S., Nadelhoffer, K.J., Peters, D.P., 2008. The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients. Front. Ecol. Environ. 6 (5), 264–272.
Grove, J.M., Locke, D.H., O'Neil-Dunne, J.P.M., 2014. An ecology of prestige in New York City: examining the relationships among population density, socio-economic status, group identity, and residential canopy cover. Environ. Manag. 54 (3), 402–419. https://doi.org/10.1007/s00267-014-0310-2.
Herreros-Cantis, P., McPhearson, T., 2021. Mapping supply of and demand for ecosystem services to assess environmental justice in New York City. Ecol. Appl. 31 (6) https://doi.org/10.1002/eap.2390.
Hsu, A., Sheriff, G., Chakraborty, T., et al., 2021. Disproportionate exposure to urban heat island intensity across major US cities. Nat. Commun. 12, 2721. https://doi.org/10.1038/s41467-021-22799-5.
Instituto Geográfico Nacional, 2023. LIDAR 2ª Cobertura (2015-2021). Infraestructura de Datos Espaciales de España (IDEE). Retrieved from [https://centrodedescargas.cnig.es/CentroDescargas/index.jsp].
Instituto Nacional de Estadística (INE), 2022. Available online: https://www.ine.pt/xportal/xmain?https://www.ine.es/nomen2/index.do?accion=busquedaRapida&subaccion=&numPag=0&ordenAnios=ASC&nombrePoblacion=vitoria&botonBusquedaRapida=Consultar+selecci%F3n.
IPCC (2007). Climate change 2007: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Untergovernment Panel on Climate Change. 2007. Cambridge University Press, Cambridge, UK.
IPCC (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:https://doi.org/10.1017/9781009157896.
Jenerette, D.G., Harlan, S.L., Stefanov, W.L., Martin, C.A., 2011. Ecosystem services and urban heat riskscape moderation: water, green spaces, and social inequality in Phoenix, USA. Ecol. Appl. 21 (7), 2637–2651. https://doi.org/10.1890/10-1493.1.
Jenerette, G.D., Miller, G., Buyantuev, A., Pataki, D.E., Gillespie, T.W., Pincetl, S., 2013. Urban vegetation and income segregation in drylands: a synthesis of seven metropolitan regions in the southwestern United States. Environ. Res. Lett. 8 (4), 044001.
Jin, K., Wang, F., Chen, D., Liu, H., Ding, W., Shi, S., 2019. A new global gridded anthropogenic heat flux dataset with high spatial resolution and long-term time series. Sci. Data 6 (1), 139.
Keeler, B.L., Hamel, P., McPhearson, T., Hamann, M.H., Donahue, M.L., Meza Prado, K. A., Wood, S.A., 2019. Social-ecological and technological factors moderate the value of urban nature. Nat. Sustain. 2 (1), 29–38.
Kraemer, R., Kabisch, N., 2022. Parks under stress: air temperature regulation of urban green spaces under conditions of drought and summer heat. Front. Environ. Sci. 10, 318.
Kremer, P., Hamstead, Z.A., McPhearson, T., 2016. The value of urban ecosystem services in new York City: a spatially explicit multicriteria analysis of landscape scale valuation scenarios. Environ Sci Policy 62, 57–68. https://doi.org/10.1016/j.envsci.2016.04.012.
Kuras, E.R., Hondula, D.M., Brown-Saracino, J., 2015. Heterogeneity in individually experienced temperatures (IETs) within an urban neighborhood: insights from a new approach to measuring heat exposure. Int. J. Biometeorol. 59 (10), 1363–1372. https://doi.org/10.1007/s00484-014-0946-x.
Langemeyer, J., Wedgwood, D., McPhearson, T., Baró, F., Madsen, A.L., Barton, D.N., 2020. Creating urban green infrastructure where it is needed–a spatial ecosystem service-based decision analysis of green roofs in Barcelona. Sci. Total Environ. 707, 135487 https://doi.org/10.1016/j.scitotenv.2019.135487.
Lanza, K., Stone Jr., B., 2016. Climate adaptation in cities: what trees are suitable for urban heat management? Landsc. Urban Plan. 153, 74–82. https://doi.org/10.1016/j.landurbplan.2015.12.002.
Lenton, T.M., Xu, C., Abrams, J.F., Ghadiali, A., Loriani, S., Sakschewski, B., Zimm, C., Ebi, K.L., Dunn, R.R., Svenning, J., Scheffer, M., 2023. Quantifying the Human Cost of Global Warming. https://doi.org/10.1038/s41893-023-01132-6.
Leong, M., Dunn, R.R., Trautwein, M.D., 2018. Biodiversity and socioeconomics in the city: a review of the luxury effect. Biol. Lett. 14 (5), 20180082.
Liu, H., Remme, R.P., Hamel, P., Nong, H., Ren, H., 2020. Supply and demand assessment of urban recreation service and its implication for greenspace planning-a case study on Guangzhou. Landsc. Urban Plan. 203, 103898 https://doi.org/10.1016/j.landurbplan.2020.103898.
Locke, D.H., Hall, B., Grove, J.M., Pickett, S.T., Ogden, L.A., Aoki, C., O'Neil-Dunne, J.P., 2021. Residential housing segregation and urban tree canopy in 37 US cities. npj Urban Sustain. 1 (1), 15.
Luo, J., Fu, H., 2023. Constructing an urban cooling network based on PLUS model: implications for future urban planning. Ecol. Indic. 154, 110887 https://doi.org/10.1016/j.ecolind.2023.110887.
Maantay, J., 2002. Mapping environmental injustices: pitfalls and potential of geographic information systems in assessing environmental health and equity. Environ. Health Perspect. 110, 161–171.
Mallen, E., Stone, B., Lanza, K., 2019. A methodological assessment of extreme heat mortality modeling and heat vulnerability mapping in Dallas. Texas. *Urban Climate* 30, 100528. https://doi.org/10.1016/j.uclim.2019.100528.

Manoli, G., Fatichi, S., Schläpfer, M., Yu, K., Crowther, T.W., Meili, N., Burlando, P., Katul, G.G., Bou-Zeid, E., 2019. Magnitude of urban heat islands largely explained by climate and population. Nature 573 (7772), 55–60.

Marando, F., Salvatori, E., Sebastiani, A., Fusaro, L., Manes, F., 2019. Regulating ecosystem services and green infrastructure: assessment of urban Heat Island effect mitigation in the municipality of Rome, Italy. Ecol. Model. 392, 92–102. https://doi.org/10.1016/j.ecolmodel.2018.11.011.

Marando, F., Heris, M.P., Zulian, G., Udías, A., Mentaschi, L., Chrysoulakis, N., Parastatidis, D., Maes, J., 2022. Urban heat island mitigation by green infrastructure in European functional urban areas. Sustain. Cities Soc. 77, 103564 https://doi.org/10.1016/j.scs.2021.103564.

Marquez-Torres, A., Balbi, S., Villa, F., 2023. Scientific modelling can be accessible, interoperable and user friendly: a case study for pasture and livestock modelling in Spain. PLoS One 18, 1–27. https://doi.org/10.1371/journal.pone.0281348.

Mascarenhas, A., Haase, D., Ramos, T.B., Santos, R., 2019. Pathways of demographic and urban development and their effects on land take and ecosystem services: the case of Lisbon metropolitan area, Portugal. Land Use Policy 82, 181–194. https://doi.org/10.1016/j.landusepol.2018.11.056.

Massaro, E., Schifanella, R., Piccardo, M., Caporaso, L., Taubenböck, H., Cescatti, A., Duveiller, G., 2023. Spatially-optimized urban greening for reduction of population exposure to land surface temperature extremes. Nat. Commun. 1–10 https://doi.org/10.1038/s41467-023-38596-1.

Nayak, S.G., Shrestha, S., Kinney, P.L., Ross, Z., Sheridan, S.C., Pantea, C.I., Hwang, S.A., 2018. Development of a heat vulnerability index for New York state. Public Health 161, 127–137. https://doi.org/10.1016/j.puhe.2017.09.006.

Olazabal, M., Feliu, E., Herranz-Pascual, M.K., Abajo, B., González-Aparicio, I., Simón-Moral, A., Alonso, A., 2012. Climate change adaptation plan of Vitoria-Gasteiz. Spain 335–347. https://doi.org/10.1007/978-94-007-4223-9_35.

Park, J., Kim, J.H., Lee, D.K., Park, C.Y., Jeong, S.G., 2017. The influence of small green space type and structure at the street level on urban heat island mitigation. Urban For. Urban Green. 21, 203–212. https://doi.org/10.1016/j.ufug.2016.12.005.

R Core Team, 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL. https://www.R-project.org/.

Reid, C.E., O'Neill, M.S., Gronlund, C.J., Brines, S.J., Brown, D.G., Diez-Roux, A.V., Schwartz, J., 2009. Mapping community determinants of heat vulnerability. Environ. Health Perspect. 117 (11), 1730–1736. https://doi.org/10.1289/ehp.0900683.

Rodríguez-Gómez, F., Fernández-Cañero, R., Pérez, G., del Campo-Ávila, J., López-Rodríguez, D., Pérez-Urrestarazu, L., 2022. Detection of unfavourable urban areas with higher temperatures and lack of green spaces using satellite imagery in sixteen Spanish cities. Urban For. Urban Green. 78 https://doi.org/10.1016/j.ufug.2022.127783.

Schell, C.J., Dyson, K., Fuentes, T.L., Roches, S. Des, Harris, N.C., Miller, D.S., Woelfle-Erskine, C.A., Lambert, M.R., 2020. The ecological and evolutionary consequences of systemic racism in urban environments. Science 369 (6509), 1–19. https://doi.org/10.1126/SCIENCE.AAY4497.

Schloerke, B., Cook, D., Larmarange, J., Briatte, F., Marbach, M., Thoen, E., … Wickham, H. (2021). GGally: Extension to 'ggplot2'.

Sebastiani, A., Marando, F., Manes, F., 2021. Mismatch of regulating ecosystem services for sustainable urban planning: PM10 removal and urban heat island effect mitigation in the municipality of Rome (Italy). Urban For. Urban Green. 57, 126938 https://doi.org/10.1016/j.ufug.2020.126938.

Stott, I., Soga, M., Inger, R., Gaston, K.J., 2015. Land sparing is crucial for urban ecosystem services. Front. Ecol. Environ. 13 (7), 387–393. https://doi.org/10.1890/140286.

Tan, P.Y., Samsudin, R., 2017. Effects of spatial scale on assessment of spatial equity of urban park provision. Landsc. Urban Plan. 158, 139–154.

Tesfamariam, S., Govindu, V., Uncha, A., 2023. Spatio-temporal analysis of urban heat island (UHI) and its effect on urban ecology: the case of Mekelle city, northern Ethiopia. Heliyon 9 (2). https://doi.org/10.1016/j.heliyon.2023.e13098.

Villa, F., Bagstad, K.J., Voigt, B., Johnson, G.W., Portela, R., 2014. A Methodology for Adaptable and Robust Ecosystem Services Assessment. 9 (3) https://doi.org/10.1371/journal.pone.0091001.

Villa, F., Balbi, S., Athanasiadis, I.N., Caracciolo, C., 2017. Semantics for interoperability of distributed data and models: foundations for better-connected information. F1000Research 6, 686. https://doi.org/10.12688/f1000research.11638.1.

Wang, J., Mcphearson, T., Zhou, W., & Cook, E. M. (2023). Comparing relationships between urban heat exposure , ecological structure, and socio-economic patterns in Beijing and New York City. Landsc. Urban Plan., 235, 104750. doi:https://doi.org/10.1016/j.landurbplan.2023.104750.

Whitlow, T.H., Pataki, D.A., Alberti, M., Pincetl, S., Setala, H., Cadenasso, M., Felson, A., McComas, K., 2014. Response to authors' reply regarding "modeled PM2.5 removal by trees in ten U.S. cities and associated health effects" by Nowak et al. (2013). Environ. Pollut. 191, 258–259. https://doi.org/10.1016/j.envpol.2014.03.035.

Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hoen, P.A., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, SA., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data 3 (1), 1–9.

Wisner, B., 2016. Vulnerability as concept, model, metric, and tool. In: Oxford Research Encyclopedia of Natural Hazard Science. https://doi.org/10.1093/acrefore/9780199389407.013.25. Issue August 2016.

Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough.' Landsc. Urban Plan., 125, 234–244. doi:https://doi.org/10.1016/j.landurbplan.2014.01.017.

Wolff, S., Schulp, C.J.E., Verburg, P.H., 2015. Mapping ecosystem services demand: a review of current research and future perspectives. Ecol. Indic. 55, 159–171. https://doi.org/10.1016/j.ecolind.2015.03.016.

Yang, J., Wang, Z.H., 2017. Planning for a sustainable desert city: the potential water buffering capacity of urban green infrastructure. Landsc. Urban Plan. 167, 339–347. https://doi.org/10.1016/j.landurbplan.2017.07.014.

Yao, J., Liu, M., Chen, N., Wang, X., He, X., Hu, Y., Chen, W., 2021. Quantitative assessment of demand and supply of urban ecosystem services in different seasons: a case study on air purification in a temperate city. Landsc. Ecol. 36, 1971–1986. https://doi.org/10.1007/s10980-020-01112-7.

Zhang, S., Landuyt, D., Verheyen, K., De Frenne, P., 2022. Tree species mixing can amplify microclimate offsets in young forest plantations. J. Appl. Ecol. 59 (6), 1428–1439. https://doi.org/10.1111/1365-2664.14158.