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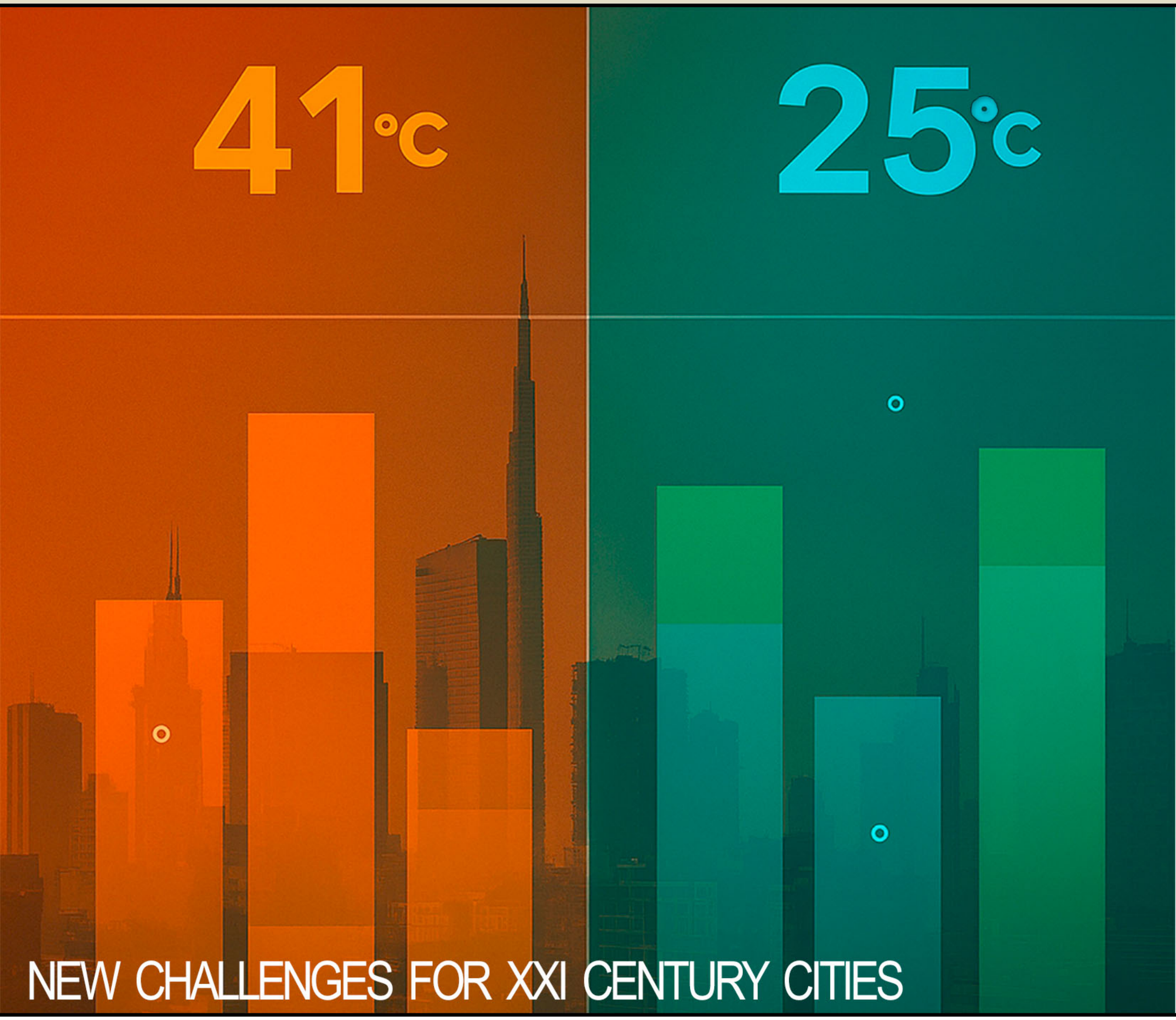

Multilevel scientific approach to impacts of global warming on urban areas, energy transition, optimisation of land use and emergency scenario

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NEW CHALLENGES FOR XXI CENTURY CITIES:

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Assessing heat stress risk to inform urban heat adaptation. A method applied in the Friuli Venezia Giulia region, Italy

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Abstract

Urban areas usually experience higher temperatures than their surroundings, especially due to impervious surfaces that absorb and re-emit solar radiation. This phenomenon is called urban heat island and occurs mainly at night. People living in urban settings are therefore particularly exposed to potential heat-related health problems caused during the hot season due to prolonged thermal discomfort conditions. This situation is likely to worsen in the future due to climate change, possibly resulting in increased health costs and socio-ecological inequalities. The socio-demographic structure of the population is key in determining the vulnerability of the population to heat stress conditions, with the weakest and most socially and economically disadvantaged being the most vulnerable. To support more targeted adaptation interventions to improve urban resilience and reduce people's heat-related risks, this study develops a heat stress index that combines hazard, exposure, and vulnerability factors. The index is applied to the urban areas of the Friuli Venezia Giulia region (Italy), making it possible to identify risk hotspots that may be prioritized for reducing risk. The factors that contribute to determining the final risk condition are analyzed and discussed, together with the possible uses of the approach to support climate adaptation planning decisions at different scales and the risk mitigation solutions that may be implemented to this aim.

Keywords

Risk assessment; Urban Heat Island; Adaptation planning

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1. Introduction

Urban areas usually experience higher temperatures than their surrounding areas, a phenomenon that is especially evident during the night hours (Oke et al., 2017). This phenomenon is called urban heat island (UHI). It is caused by the significant presence of impermeable surfaces in urban environments, such as concrete and asphalt, which absorb heat from solar radiation during the day to a very much greater extent than vegetated and permeable areas. The stored heat is then released very gradually back into the atmosphere, contributing to increasing local temperatures and limiting the natural night-time temperature drop within built-up areas (Yu et al., 2020). The heat produced by vehicle combustion processes, industrial activities, and air conditioning systems also contributes to warming urban environments (Kim et al., 2022).

Since a large portion of the population is concentrated in urban settings that likely experience (more or less intense) heat islands, which exacerbate the negative effects of summer high temperatures, many people are overexposed to potential health problems (e.g., cardiovascular and respiratory disorders, heat stroke (Reiners et al., 2023)) caused by prolonged thermal discomfort conditions during the hot season.

This situation is destined to worsen in the coming years due to the progressive rise in temperatures caused by climate change, with Italy located in an area particularly sensitive to this problem. This could lead to an increase in both health costs and socio-ecological inequalities that make certain population groups more prone to heat-related impacts. These inequalities are notoriously linked to situations of disadvantage from both a social (i.e., people with disadvantaged socio-economic conditions) and an environmental (i.e., people living in areas prone to UHI) point of view.

On the one hand, the socio-demographic structure of the population has a significant influence in determining people's vulnerability conditions. The more vulnerable population groups during heat waves – also recognized by the Italian government (Italian Ministry of Health, n.d.) – include: the elderly, due to greater sensitivity to heat, a reduced thirst stimulus, and less efficient thermoregulation mechanisms; infants and children, due to a reduced capacity for thermoregulation and the inability to express any discomfort related to environmental conditions; the economically and socially disadvantaged people, as conditions of poverty (e.g., lower incomes) and isolation (e.g., language/cultural barriers) may reduce awareness of risks and limit the access to emergency/mitigation solutions (e.g., air-condition).

On the other hand, living in an urban area that is particularly prone to be affected by heat island phenomena makes the population of that area more vulnerable, as they are potentially exposed to higher temperatures for a longer time, given that this phenomenon maintains high(er) temperatures even during the night when they should naturally decrease to more tolerable levels. This leads urban populations to experience more prolonged heat stress/thermal discomfort conditions during summer hot periods with enhanced potential to suffer health impacts, since the longer the temporal exposure to heat stress conditions, the less the people's ability to cool off and the recovery time for the body (Logan et al., 2020). However, UHI may not only cause health impacts but also increase economic expenditure, since the longer the time with high ambient temperatures, the longer artificial air conditioning systems are required to function, leading to more energy consumption and energy bills increase (Santamouris, 2020).

It is therefore extremely urgent for Italian regions and cities to adopt and implement policies and measures aimed at mitigating the risks associated with heat stress due to the overheating of urban areas, which can be achieved through the reduction of the vulnerability condition of people and/or of the areas in which they live, for example through green spaces that counteract urban heat accumulation and provide cooler air flows to surrounding areas and high-albedo materials that better reflect solar radiation preventing surface overheating (Stiuso, 2025).

Within this context, this work aims to propose and test a spatially explicit risk index to determine the risk of urban populations being negatively affected by heat stress-related impacts. Climate-related spatial risk assessments are of undeniable importance to support adaptation policies, especially in the framework of urban/spatial planning (e.g., Maragno et al., 2020), where the geographical dimension plays a key role in the spatial allocation of adaptation solutions and, consequently, their benefits and beneficiaries (e.g., Ceci et al., 2023). Various methods for developing risk indices (or variations of them, e.g., territorial vulnerability indices) exist and have been applied worldwide to various hazards (e.g., Jibhakate et al., 2023; Beltramino et al., 2022), including for assessing heat-related urban population risks in Italy and beyond (e.g., Longato et al., 2025; Ellena et al., 2023; Pappalardo et al., 2023).

The proposed index is developed according to the latest IPCC (i.e., Intergovernmental Panel on Climate Change) framework by accounting for the hazard, exposure, and vulnerability factors that concur to determine the risk condition of city inhabitants. Overall, the application of this index can provide an overview of the different risk conditions affecting people who live in an urban context and can therefore support decisions that target and prioritize risk mitigation interventions within high-risk hotspots, while unveiling the main socio-demographic and environmental conditions that most concur to the final risk condition. The index is applied to the urban areas of the Friuli Venezia Giulia (FVG) region, revealing which urban settings, and what specific areas within them, are characterized by higher risk conditions that deserve special attention for risk reduction strategies and adaptation interventions.

2. Method

2.1 Rationale and study area

The risk index is developed by combining the three factors that contribute to risk: hazard, exposure, and vulnerability.

According to the latest definitions proposed by the Intergovernmental Panel on Climate Change (IPCC, 2022), hazard refers to the possible occurrence of a physical event or trend (natural or human-induced) that may have negative consequences on exposed and vulnerable elements. Exposure refers to the presence of elements in an area that may be affected by such an event, i.e., they are exposed because they are located in a potentially hazardous area. Vulnerability refers to the propensity or predisposition of the exposed elements to be negatively impacted in light of the occurrence of the hazardous event.

In this case, the hazard is defined in relation to the occurrence of periods with (potentially hazardous) high temperatures, the exposure in relation to the amount of population exposed to potentially high(er) urban temperatures and heat stress conditions, and the vulnerability in relation to the degree of resilience and/or fragility (i.e., to heat stress) of the population itself and of the urban environment in which they reside. The geographical unit of reference for which the assessments are carried out is represented by the census unit areas (i.e., the so-called census sections in Italy) for which population data is collected.

The study area is represented by the FVG region, located in the north-eastern part of Italy. The regional area includes the Alpine region bordering Austria and Slovenia, the hilly karst area between the cities of Trieste and Gorizia, and a floodplain and a coastal area overlooking the North Adriatic Sea in which most of the population lives. Since located between the Alps and the Mediterranean, two climate change hotspot areas, its climate profile is characterized by above-average temperature increase and more and more frequent weather extremes, including heatwave periods resulting in thermal discomfort conditions, especially during summer, which are projected to worsen in the future (see ARPA FVG, 2018 and ARPA FVG, 2023 for more information). This makes the FVG region an appropriate illustrative example to test and apply the proposed risk index.

To limit the assessment to the areas that are plausibly exposed to potentially hazardous high temperatures during the summer season, it was decided to include only the urban settings located in the regional area characterized by an average maximum summer temperature of at least 25° (Fig.1) according to the historical data provided by the Regional Agency for the Environment (ARPA FVG, n.d). To do so, the selected census sections are the ones that intersect the urban footprint areas (according to the regional land use map) that satisfy the above-defined temperature threshold and that are coded as "urban centres", "inhabited settlements", or "industrial zones", thus leaving out those classified as "scattered houses" that predominantly correspond to agricultural and/or non-inhabited areas.

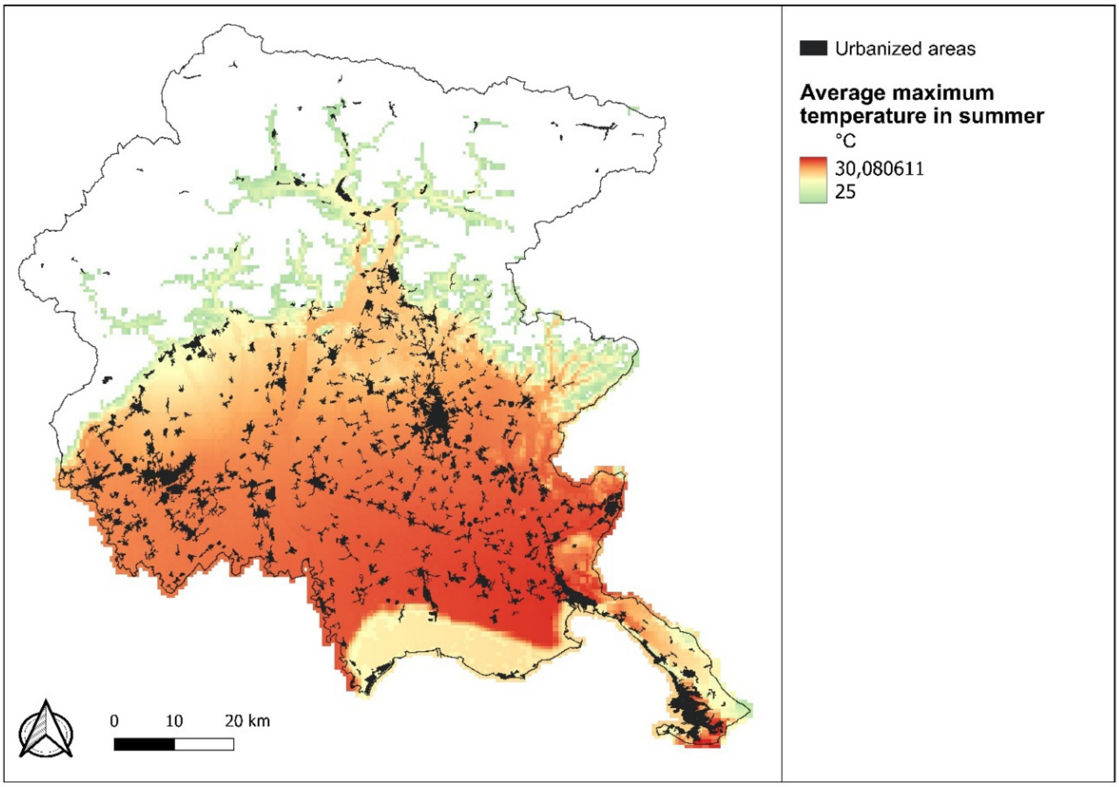

Fig.1 The territory of the FVG region characterized by an average maximum temperature during the summer period (i.e., months of June, July, and August) of at least 25° according to the 1991-2020 historical series. White areas are the ones characterized by temperature values below this threshold, corresponding to medium- to high-mountain regions. Source: Authors' elaboration based on monthly data produced by ARPA FVG (ARPA FVG, n.d.)

2.1 Hazard calculation

For the calculation of the hazard indicator $H_{clim.heat,j}$, it was used the average number of days per year with temperature exceeding 30° (Fig.2) as representative weather-climate hazard data, also known as 'hot days'. The formula (1) used for the calculation of the (normalized) indicator is as follows:

$$H_{clim.heat,j} = \frac{hot\ days_j\ -\ min(hot\ days_j)}{max(hot\ days_j)\ -\ min(hot\ days_j)} \quad (1)$$

Where $hot\ days_j$ represents the value of the average number of 'hot days' per year within the census section *j*.

2.2 Exposure calculation

The density of inhabitants, calculated using the data on the resident population of the last population census survey of 2021 by the Italian National Institute of Statistics, was used to determine the population exposure and calculate the related indicator $E_{pop,j}$. The variable 'density of inhabitants' was preferred to the total number of inhabitants because, due to the way census sections are geographically defined with the sections in urban core areas being very much smaller than the others, it provides more suitable information to define the concentration of the (exposed) elements in the territory (e.g., in cases of similar numbers of inhabitants in both a peri-urban census section and an urban core census section, the ones living in the peri-urban one are spread over a much larger area, hence with a much lower density, which means that the exposed element - the inhabitants - is much less spatially concentrated than in the urban census section). The formula (2) for the calculation of the (normalized) indicator is as follows:

$$E_{pop,j} = \frac{dens_{pop,j} - min(dens_{pop,j})}{max(dens_{pop,j}) - min(dens_{pop,j})} \quad (2)$$

Where $dens_{pop,j}$ represents the value of the density of inhabitants (per hectare) within the census section *j*.

2.3 Vulnerability calculation

The vulnerability factor was assessed by taking into consideration both socio-demographic and environmental factors that may concur to influence the vulnerability profile of the exposed element, i.e., the inhabitants. Consequently, the vulnerability indicator $V_{pop.heat,j}$ was calculated by combining two sub-indicators, one relating to the vulnerability according to the socio-demographic profile of the population (i.e., social vulnerability) and the other according to the propensity to suffer from UHI effects of the area in which they reside that may exacerbate heat impacts on people. The formula (3) used to combine the two sub-indicators is as follows:

$$V_{pop.heat,j} = \frac{V_{soc,j} + V_{heat,j}}{2} \quad (3)$$

Where $V_{soc,j}$ represents the value of the social vulnerability indicator within the census section *j*, $V_{heat,j}$ represents the value of a purposely developed UHI-related vulnerability indicator within the census section *j*.
To calculate the social vulnerability indicator, several representative socio-demographic variables were calculated and combined to map the population groups considered most vulnerable to heat stress, according to the population information available in the 2021 national population census survey. These variables are: percentage of inhabitants considered vulnerable according to age (young children < 5 years and elderly people > 65 years); percentage of inhabitants considered vulnerable according to the economic profile (i.e., unemployed people in working-age); percentage of inhabitants considered vulnerable due to possible social isolation and language barriers (i.e., foreign people). The formula (4) for calculating the (normalized) indicator is as follows:

$$V_{soc,j} = \frac{\frac{V_{soc1,j} - min(V_{soc1,j})}{max(V_{soc1,j}) - min(V_{soc2,j})} + \frac{V_{soc2,j} - min(V_{soc2,j})}{max(V_{soc2,j}) - min(V_{soc2,j})} + \frac{V_{soc3,j} - min(V_{soc3,j})}{max(V_{soc3,j}) - min(V_{soc3,j})}}{3} \quad (4)$$

Where $V_{soc1,j}$, $V_{soc2,j}$ and $V_{soc3,j}$ represent the percentage values of the three selected social variables (above-mentioned) within the census section *j*.
To calculate the UHI-related vulnerability indicator, a qualitative pixel-based index was developed by combining the satellite-derived Land Surface Temperature (LST) data and a spatial simulation of the potential cooling effects provided by the surrounding natural and semi-natural ecosystems. This index (from now on called 'UHI vulnerability index') was proposed and tested by Longato & Maragno (2024) at the city scale to improve UHI analysis with remotely-sensed data since the use of LST allows the detection of Surface UHI (SUHI) only and is not (always) able to capture the potential flows of cooler air flowing from the surrounding ecosystems that can partly counteract heat islands. SUHI in fact only refers to surface temperatures, namely how hot is an object if you touch it, while what mostly influences thermal perception and discomfort for people is the temperature of the air above the ground, up to the level of buildings and tree tops, which is influenced

by several other factors besides surface temperatures, including near-surface air flows (e.g., Rocha et al., 2024). The proposed UHI vulnerability index thus integrates both a sensitivity – LST-derived SUSHI – and a coping capacity – potential cooling spatial effects of ecosystems – factor to account for multiple factors contributing to urban temperature variations.

Concerning the sensitivity factor, it was decided to use a historical series of LST (2013 to 2023). Using the Google Earth Engine Platform, which makes it possible to overcome traditional shortcomings concerning the use of large-scale and muti-temporal series of satellite data (e.g., time processing (Isola et al., 2023)) a script was used to automatically extract the pixel-based average LST value from the Landsat 8 satellite image series using as a reference period the summer months (i.e., June, July, and August) from 2013 to 2023. This way, it was possible to detect the multi-year average behaviour of surface temperatures during summer, avoiding using only one or a few images that could not have fully represented the LST spatial variability normally expected in summer. Moreover, given the regional scope of the analysis, it was possible to cover all the regional territory since the use of many images allowed to minimize the lack of LST data at the pixel level due to the (more or less frequent) presence of clouds. To this aim, the script was developed to mask out the pixels covered by clouds in each satellite image used for calculating the average value. A total of 303 satellite images (i.e., distributed across the tiles covering the case study area) were detected during the reference period and used to calculate the average value of LST. It is worth noting that not all the resulting pixel average values are calculated using the same number of satellite images due to the spatial variability and frequency of clouds that may have affected some areas more than others, reducing the number of usable satellite images in specific pixel areas.

Subsequently, the distribution of the LST values was used to identify five vulnerability classes (with scores from 1 – least vulnerable, to 5 – most vulnerable) according to five progressive temperature ranges obtained by categorizing the temperature values using the Natural Breaks statistical method. Given the large scale of the analysis, leading to a large variability of air temperature values, to account for the influence of air temperature variation on LST it was decided to subdivide the regional area into sectors and to categorize the LST values (for subsequently assigning the vulnerability classes) separately for each sector. This was done according to five different ranges of average maximum summer air temperatures (see Fig.1 for the spatial distribution), namely: areas between 25° (the lowest value for including an area into the analysis) and 26°; areas between 26° and 27°; areas between 27° and 28°; areas between 28° and 29°; areas above 29° (the maximum peak recorded in the region is slightly above 30°). Tab.1 shows the LST (range) classes and the corresponding vulnerability scores assigned according to the regional sectors identified.

	Sector 1: areas with air temp. 25° to 26°	**Sector 2: areas with air temp. 26° to 27°**	**Sector 3: areas with air temp. 27° to 28°**	**Sector 4: areas with air temp. 28° to 29°**	**Sector 5: areas with air temp. > 30°**	**LST-related vulnerability score**
1st LST class (lowest sensitivity)	< 28.02°	< 29.46°	< 32.06°	< 33.75°	< 34.46°	1 (least vulnerable)
2nd LST class	28.02° to 30.51°	29.46° to 32.10°	32.06° to 34.44°	33.75° to 35.93°	34.46° to 36.73°	2
3rd LST class	30.51° to 32.58°	32.10° to 34.48°	34.44° to 36.60	35.93° to 38.22°	36.73° to 38.51°	3
4th LST class	32.58° to 34.72°	34.48° to 37.94°	36.60° to 39.45°	38.22° to 41.24°	38.51° to 41.10°	4
5th LST class (highest sensitivity)	> 34.72°	> 37.94°	> 39.45°	> 41.24°	> 41.10°	5 (most vulnerable)

Tab.1 Land Surface Temperature (range) classes and corresponding vulnerability scores assigned in each regional sector identified according to air temperature variability

Concerning the coping capacity factor, first, the potential to provide cooling effects through the local climate regulation service was assessed for the regional ecosystems mapped in the regional Habitat Map using the scoring matrix developed by Burkhard and colleagues (2014). In this matrix, qualitative scores (from 0, no relevant potential, to 5, highest potential) are assigned to reflect the potential to supply ES by different ecosystems. According to the scores assigned to the local climate regulation service, the highest cooling potential (score of 5) is provided by woodlands, followed by shrublands and agricultural areas with significant natural elements, arable land, natural grassland, pastures, permanent crops, and urban green areas (i.e., see the ES potential matrix in Burkhard et al. (2014) for more details).

Second, the (omnidirectional) spatial extent of the cooling effects was determined using standard distances from the literature, namely a buffer of 100 linear meters from ecosystem patches smaller than 2 hectares and 250 linear meters from patches larger than 2 hectares (Geneletti et al., 2016). Each cooling buffer was assigned the corresponding cooling potential score of the providing ecosystem patch.

Third, the spatial intersection between the urban areas and these buffers was computed to identify the ones potentially benefitting from the cooling effects provided by ecosystems, accounting for the different ES (cooling) potentials and related scores (i.e., if an area benefits from more than one cooling effect, the ones with the highest potential – and score – is kept for that area) that are assumed to correspond to different cooling intensity potentials in the benefitting areas.

Finally, as done for the sensitivity factor, the spatial distribution of the cooling buffers was used to assign five vulnerability classes (with scores from 1 – least vulnerable; to 5 – most vulnerable) to the urban areas according to their potential to benefit (or not) from more or less intense cooling effects from the surrounding ecosystems, corresponding to, e.g., a null coping capacity (the most vulnerable situation) in case of not benefitting from any cooling effect; or the highest coping capacity (the lest vulnerable situation) in case of benefitting from the most intense cooling effect. Tab.2 shows the vulnerability scores assigned to the different situations concerning the coping capacity factor.

Cooling intensity potentials (qualitative score) benefitted by urban areas	Vulnerability score
Areas benefitting from cooling effects with very high (5) cooling intensity potential (highest coping capacity)	1 (least vulnerability)
Area benefitting from cooling effects with high (4) cooling intensity potential	2
Areas benefitting from cooling effects with medium (3) cooling intensity potential	3
Areas benefitting from cooling effects with low (1) to moderate (2) cooling intensity potential	4
Areas not benefitting from any cooling effect (null coping capacity)	5 (most vulnerable)

Tab.2 Cooling intensity potentials benefitted by urban areas (spatial intersection with cooling buffers) and corresponding vulnerability scores assigned

Once both the sensitivity and coping capacity factors were assessed, the pixel-based UHI vulnerability index was calculated by combining them using the weighted sum method and the weights proposed by Longato & Maragno (2024), namely a relatively higher weight of 0.6 for the sensitivity factor (i.e., LST-derived SUSHI) and a relatively lower weight of 0.4 for the coping capacity factor (i.e., the cooling intensity potential provided by surrounding ecosystems to the benefit of urban areas).

Using the computed UHI vulnerability index, the formula (5) for calculating the (normalized) UHI-related vulnerability indicator is as follows:

$$V_{heat,j} = \frac{V_{UHI,j} - min(V_{UHI,j})}{max(V_{UHI,j}) - min(V_{UHI,j})} \quad (5)$$

Where $V_{UHI,j}$ represents the average value of the pixel-based UHI vulnerability index calculated within the census section *j*.

2.4 Risk calculation

The hazard, exposure, and vulnerability indicators were combined to calculate the final risk index $R_{pop.heat,j}$ depicting the (urban) population heat stress risk using the formula (6):

$$R_{pop.heat,j} = H_{clim.heat,j} * E_{pop,j} * V_{pop.heat,j} \tag{6}$$

Where $H_{clim.heat,j}$ represents the value of the hazard indicator within the census section *j*, $E_{pop,j}$ the value of the population exposure indicator within the census section *j*, and $V_{pop.heat,j}$ the value of the population vulnerability indicator within the census section *j*.

3. Results

The map (Fig.2) of the distribution of the climatic variable used to calculate the hazard indicator (average number of days per year on which the temperature exceeds 30° (ARPA FVG, n.d.)) shows that the lowland areas, especially in the eastern part of the region, are those most affected (up to more than 50 days). However, the entire lowland and Karst areas experience a high number (>35) of days per year with temperatures above 30°.

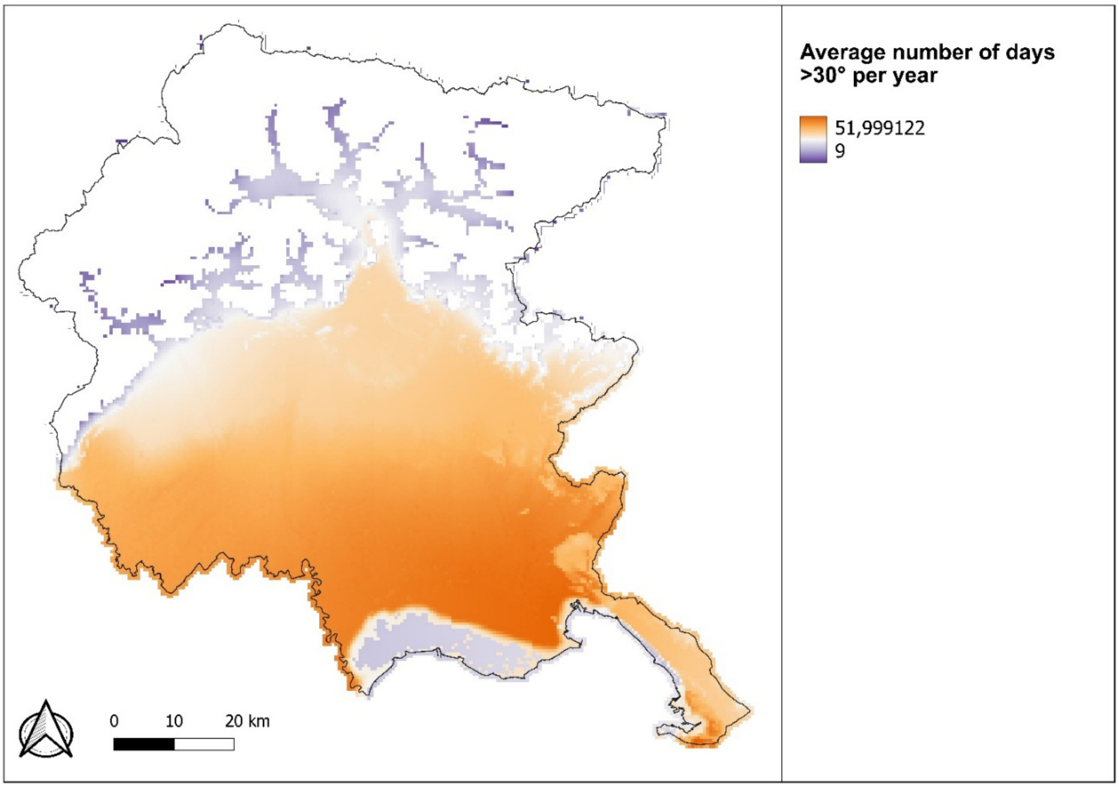

Fig.2 Distribution of the average number of days per year on which the temperature of 30° is exceeded (historical series 1991-2020; data used for calculating the hazard indicator). White areas are excluded from the analysis, corresponding to medium- to high-mountain regions. Source: Authors' elaboration based on the map produced by ARPA FVG (ARPA FVG, n.d.)

Concerning the variable used to calculate the exposure indicator (population density), it can be seen that this is commonly higher in the region's main cities (i.e., provincial capitals, but also in some medium-sized towns), with some differences in distribution from city to city (e.g., in Trieste the highest values are found in the most central areas, while in Udine especially in the first belt outside the historic centre) (Fig.3).The distribution of the variables used to calculate the social vulnerability indicator (i.e., % of inhabitants <5 years or >65 years, % of unemployed, % of foreigners) is instead more heterogeneous (Figures 4, 5, and 6), although in all the three cases there is a slight (regional-scale) tendency to concentrate the highest values towards the more peripheral urban areas or, in any case, not within the most central census sections within the larger urban centres.

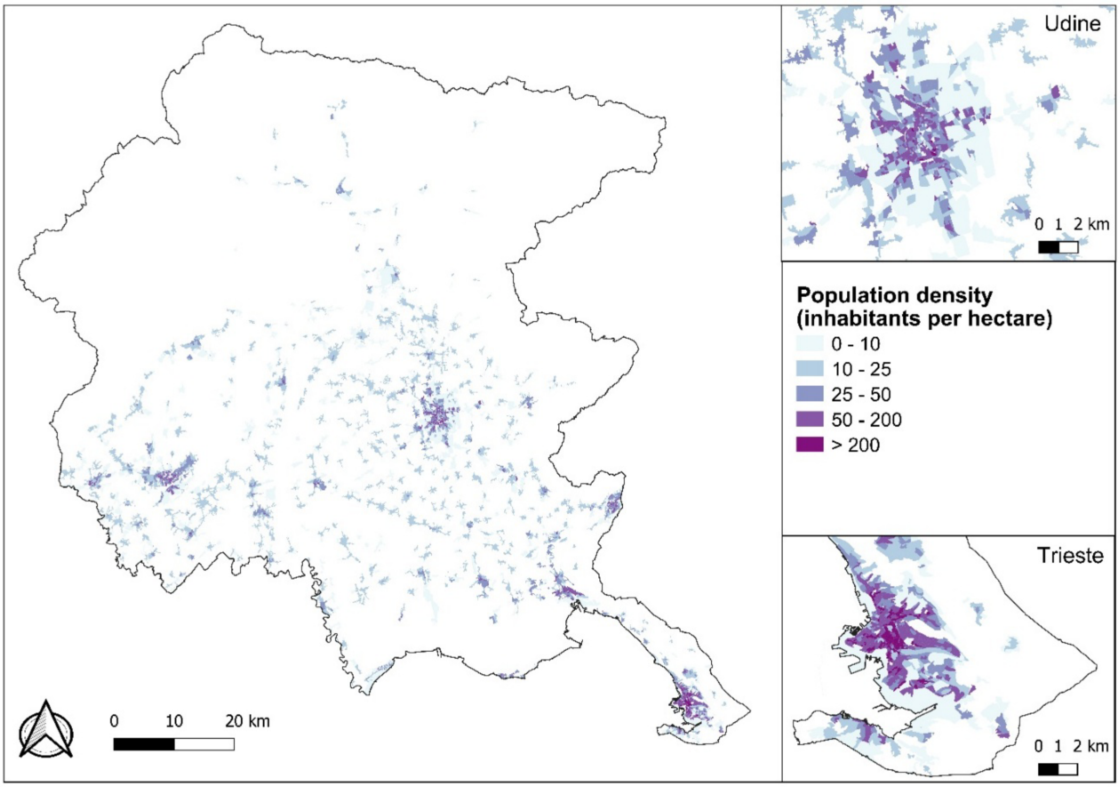

Fig.3 Distribution of population density by census section (data used for calculating the exposure indicator). Source: Authors' elaboration based on 2021 national census survey data

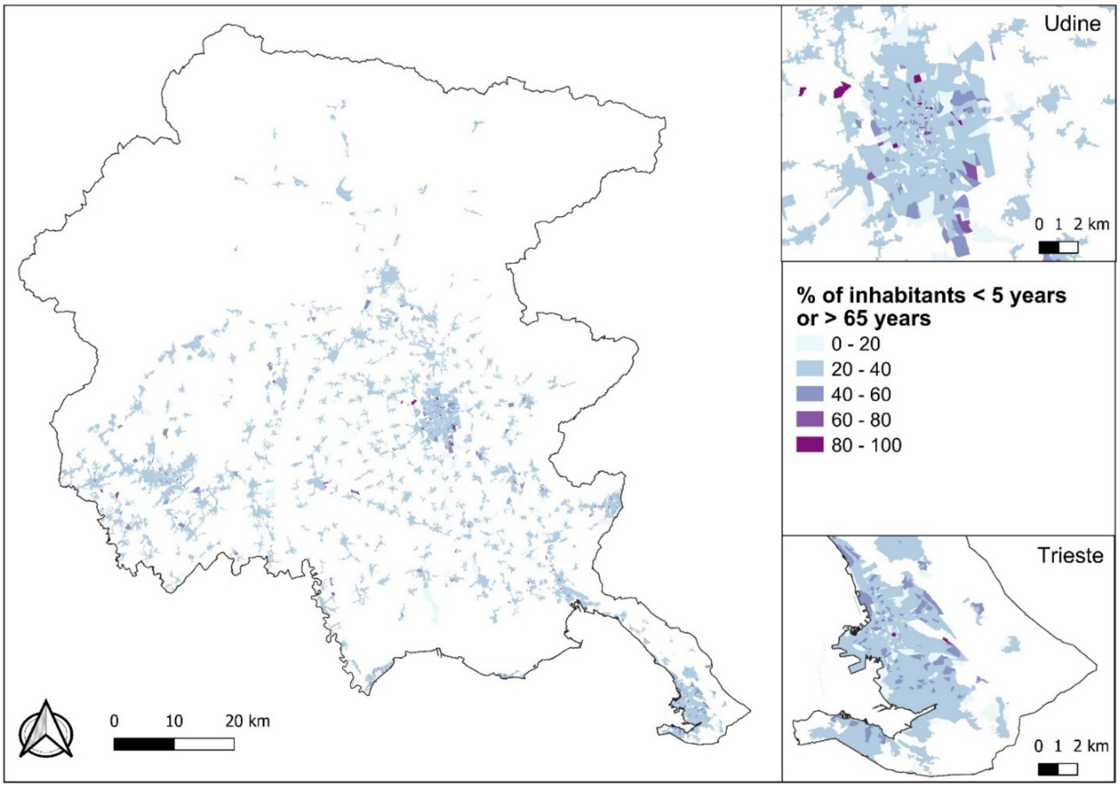

Fig.4 Distribution of the percentage of inhabitants considered most vulnerable according to age (children < 5 and elderly > 65 years) by census section (data used to calculate the vulnerability indicator). Source: author's elaboration based on 2021 national census survey data

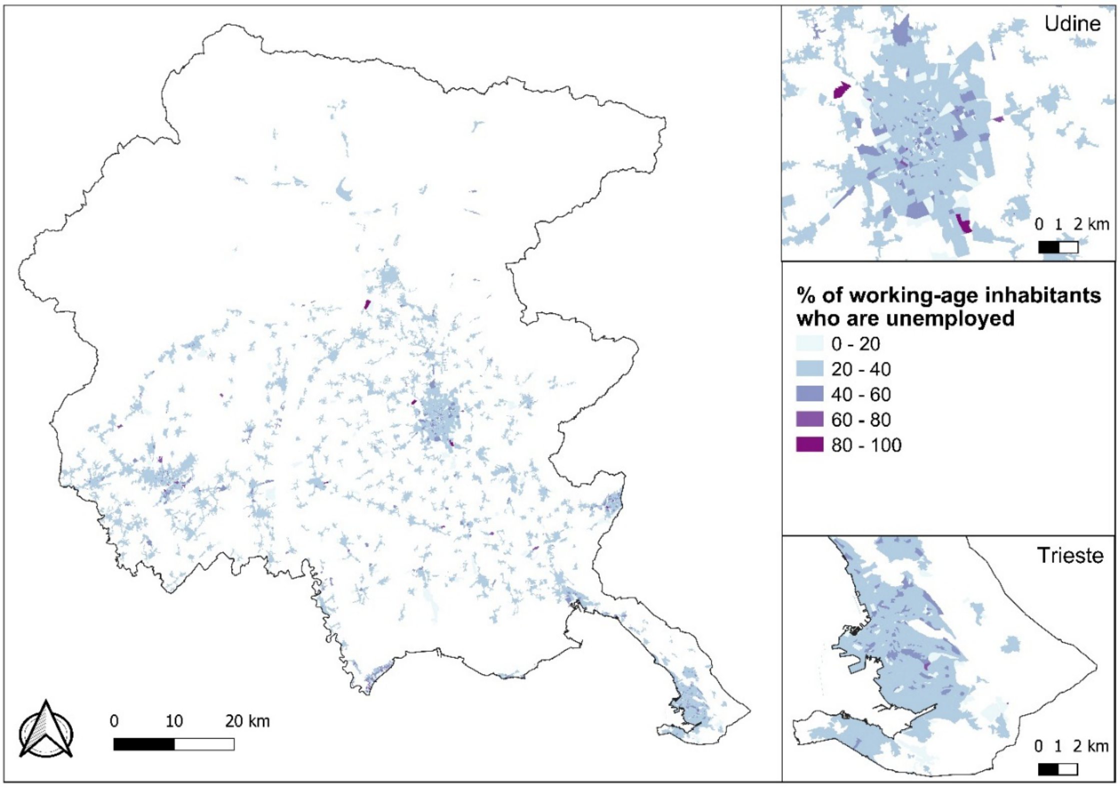

Fig.5 Distribution of the percentage of working-age inhabitants who are unemployed by census section (data used to calculate the vulnerability indicator). Source: author's elaboration based on 2021 national census survey data

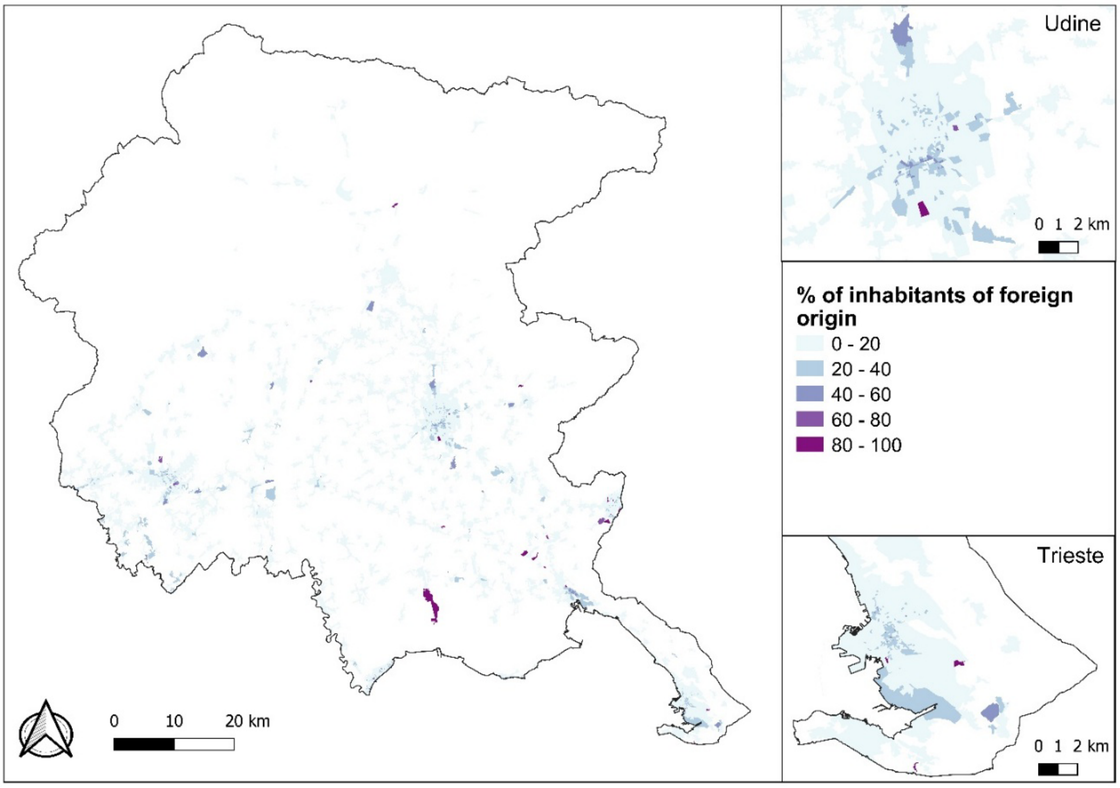

Fig.6 Distribution of the percentage of inhabitants of foreign origin by census section (data used to calculate the vulnerability indicator). Source: author's elaboration based on 2021 national census survey data

As regards the proposed index developed to calculate the UHI-related vulnerability (Fig.7), unsurprisingly the clusters of highest values are especially found in the larger towns with a dense urban fabric (e.g., Trieste, Udine, Gorizia, and to a much lesser extent in Pordenone); moderate to high values are however also found in many smaller towns and urbanized areas, especially in the south-eastern part of the region and, less widely, in the south-western part.

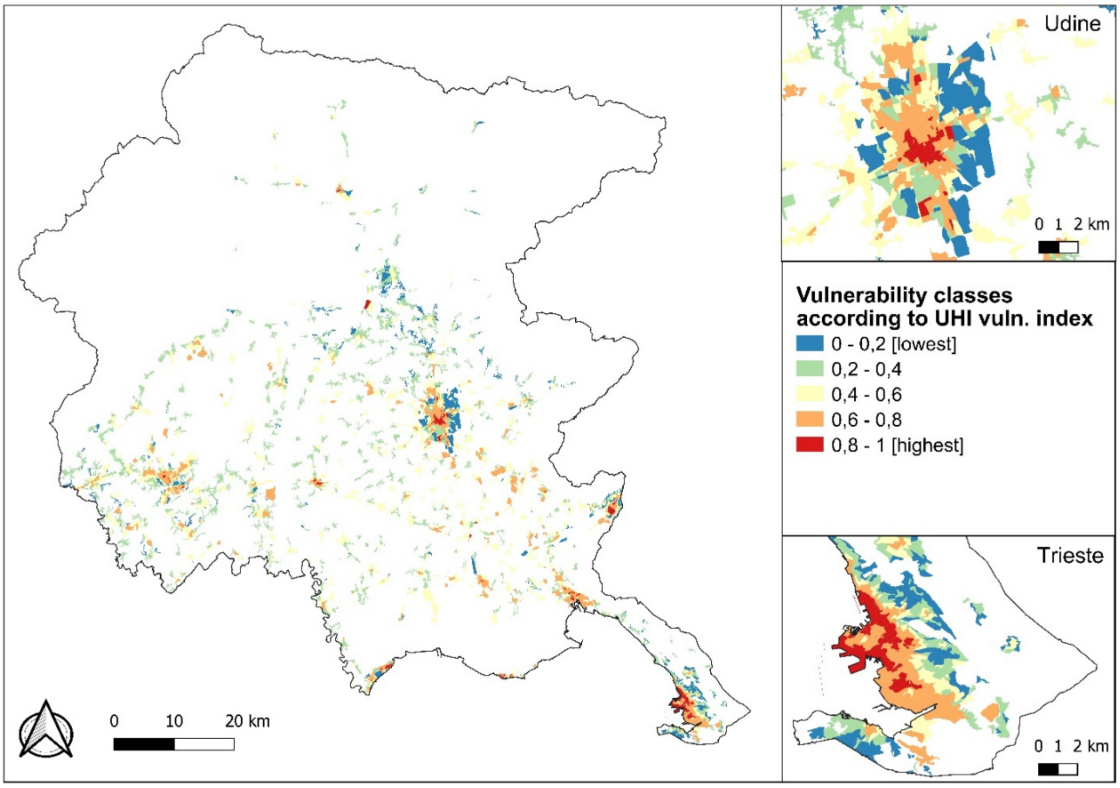

Fig.7 Distribution of the average value of the UHI vulnerability index by census section. Source: Author's elaboration

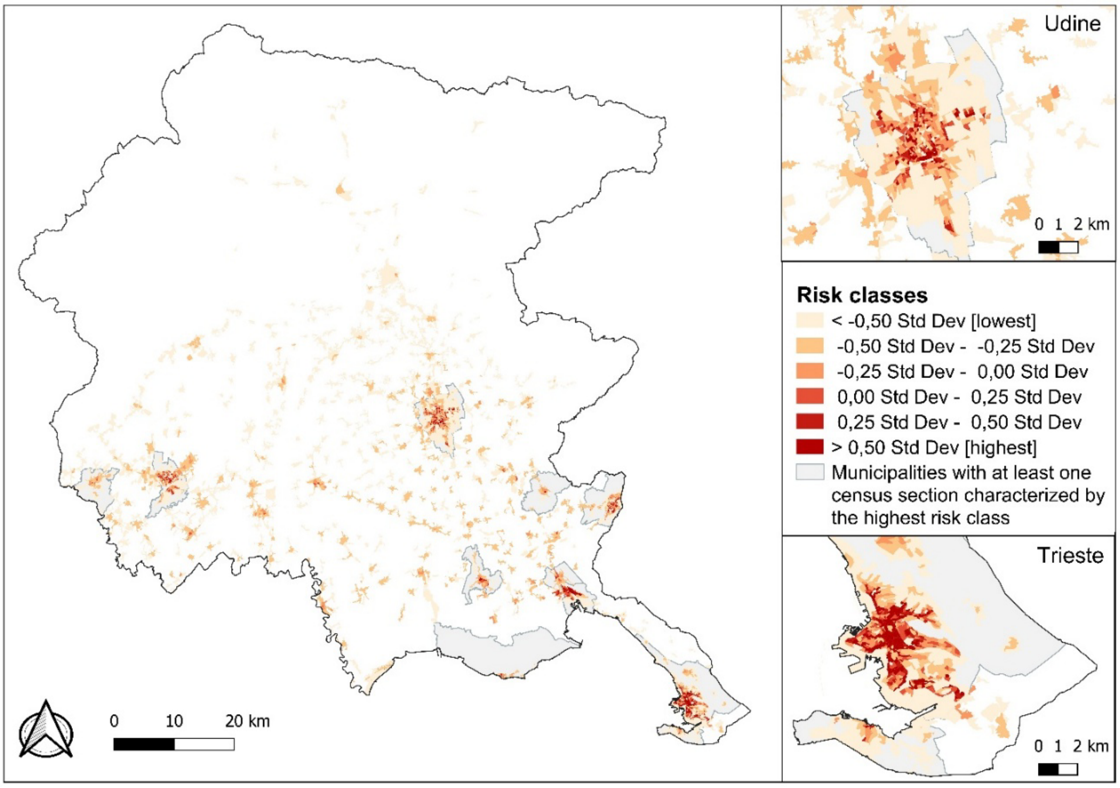

Fig.8 Distribution of the final risk classes/conditions by census section (based on the standard deviation from the average value of the risk index); the higher the standard deviation, the higher the risk condition. Source: Author's elaboration

Finally, the spatial distribution of the final risk index that combines all the variables and indicators presented above (Fig.8), in which the highest values (i.e., well above the standard deviation from the average) correspond to the highest risk conditions, makes it possible to identify the areas (census sections) in which the level of risk is potentially greater. These are concentrated within the largest urban areas (e.g., the four provincial capitals plus the medium-sized city of Monfalcone), but, in some cases, even relatively minor urban centres are characterized by at least one census section with the highest risk level (e.g., Grado, Cormons, and Ronchi dei Legionari to mention those with the smallest number of inhabitants).

4. Discussion and conclusions

This study presented a method to develop and test a risk index to assess the risk of urban populations being negatively affected by heat stress-related impacts, revealing the urban areas that show the major risk conditions according to both socio-demographic and environmental factors. The index is applied to assess the risk within the urban areas located in the FVG region, combining data and indicators that refer to the three risk components based on the IPCC framework: hazard (i.e., climate data), exposure (i.e., population distribution data), and vulnerability (i.e., people's socio-demographic characteristics and their potential to be affected by UHI effects). Main challenges and limitations of the proposed method that could affect its replicability and applicability include the availability of reliable input data needed to perform the assessment (e.g., fine-scale climate hazard data such as those available in the FVG region may not be available in other contexts) and the frequency with which they are updated. The latter aspect is especially valid for the socio-demographic data used to assess the social component of vulnerability, whereas, regarding UHI vulnerability, the use of satellite data ensures continuously updated information. Given the non-static nature of population dynamics, which may result in changes of the risk conditions and distribution over time, these types of assessment should indeed rely on regularly updated data, which are instead provided (in Italy) every 10 years through official national census surveys, often released several years after the reference year of the survey.

By combining hazard, exposure, and vulnerability metrics, the resulting risk index shows the spatial distribution of the major urban risk hotspots, which are the results of relatively high(er) hazard, exposure, and/or vulnerability conditions. However, these can contribute to the final risk in different terms across the various regional urban contexts, according to the local specificities.

To provide an overview of which variables related to the hazard, exposure, and vulnerability factors have a more or less systematic and strong relationship with the overall risk index (and, consequently, with the final risk condition), a correlation analysis (Pearson's method) was carried out between them and the final risk index. This was done at both the regional level and separately for the four capital municipalities as an example, to show how in different areas there may be different prevailing factors that determine the final risk condition (Tab.2).

Case study area analyzed	Climate hazard (days per year with T >30°)	Population exposure (population density)	Social vulnerability (% of young children and elderly)	Social vulnerability (% of unoccupied)	Social vulnerability (% of foreigners)	UHI-related vulnerability (UHI vulnerability index)
Whole region	0.0817	0.9471	0.0054	0.1154	0.2760	0.4367
Trieste	0.3551	0.9272	-0.1361	0.1225	0.5584	0.5200
Udine	-0.1199	0.9832	0.0250	0.2188	0.3822	0.4746
Pordenone	-0.1130	0.9663	0.1212	0.1689	0.2942	0.4284
Gorizia	-0.3070	0.9719	0.0011	0.1458	0.1352	0.5434

Tab.2 Correlation coefficients resulting from the correlation analysis (Pearson's method) between the value of the single variables and that of the final risk index. Negative values represent a negative correlation (the closer to the value of -1, the higher the negative correlation), while positive values represent a positive one (the closer to the value of +1, the higher the positive correlation). Values close to 0 represent a very low or almost null correlation

From the correlation coefficients obtained, it can be seen that the variable ‘population density’ is the one most correlated with the overall risk condition in all the cases analyzed (positive and highly significant correlation). It can therefore be stated that an increase in density almost always corresponds to an increase in the level of risk, a fact that well explains the role of exposure in determining the risk (e.g., an area may be located in a highly dangerous and vulnerable zone, but if the number of exposed elements is very low, the level of risk will also be relatively low), similarly to what found in other contexts in which a similar assessment method was applied (e.g., Longato et al., 2025). In contrast, at the regional scale, there is a very low correlation between the hazard variable and the final risk. At the municipal level, in the four municipalities analyzed, the trend is discordant and of variable direction. This confirms that if a place is located in an area with a higher climate hazard, this does not mean that the risk for that area is automatically higher than that of other places characterized by lower hazard conditions. As concerns the socio-demographic variables, the one that is most correlated (positively) with the final risk is generally the percentage of foreigners (higher in Trieste, lower in Gorizia), followed by the percentage of unemployed and that of young children and the elderly (the latter being insignificant in all cases and negative in Trieste). This means that, in almost all cases, one is more likely to encounter a higher risk condition when there is a relatively high percentage of foreigners compared to the other two variables. However, while these results may offer a general overview at the regional or whole city scale, further investigation of socio-demographic aspects and their contribution to the final risk condition are needed at the more local scale (i.e., intracity), since very different situations may exist from one city area to another such as already found in other similar contexts (e.g., Padova (Pappalardo et al., 2023)). Finally, vulnerability to the heat island phenomenon is always positively correlated in a moderately significant manner in all cases (almost always more significantly than the socio-demographic vulnerability), highlighting the importance of having climate-resilient places to decrease the population risk condition.

In this regard, in addition to social and economic policies and initiatives that can be deployed to support the most disadvantaged population groups (e.g., risk awareness raising activities, economic incentives for the installation/use of cooling solutions in buildings, the opening of climate refuges during hazardous weather conditions, etc.), the implementation of transformative adaptation interventions in cities to mitigate the heat island phenomenon represents one of the greatest challenges for urban/territorial plans and policies (Aflaki et al., 2017). To this aim, both green and grey interventions can be applied to cool down local temperatures and mitigate UHI. Through green interventions (i.e., nature-based solutions), generally speaking, vegetation is used to provide cooling through shading and evapotranspiration (Park et al., 2021). Examples of solutions of this type in urban areas include green roofs that lower temperatures in buildings during summer through enhanced insulation and evapotranspiration, and the creation or restoration of urban forests, parks, and green spaces that provide fresh air to the surroundings, among others. Grey solutions instead may include cool roofs and pavements that use specific surface materials characterized by a higher albedo compared with traditional ones, which consequently absorb lower rates of heat and attenuate the heat island effect.

The use of the proposed risk index could be useful above all to identify the priority areas where such interventions should be promoted with more urgency, concentrating resources and efforts so that they are as effective as possible in terms of reducing population risks and the associated social impacts and costs, a fundamental aspect in times of financial constraints and high competition between different land uses. Prioritizing the implementation of a solution in an area characterized by higher risk conditions may likely provide more benefits (than in less risky areas) in terms of, i.e., a higher number of exposed and/or vulnerable people that can benefit from it, reducing their risk and potentially more effectively decreasing the impacts - including health and economic - at the city scale once a hazardous event occurs. For this reason, the proposed index can be used to support the prioritization of adaptation interventions in relevant adaptation policies and decision-making processes.

The regional case study presented in this work aims to test the feasibility of applying the proposed method for assessing risk in large-scale areas, as well as to showcase its potential for multi-scalar applications. On the one hand, at the local scale, the proposed risk assessment can support municipalities in identifying the most problematic urban areas that are potentially characterized by higher population heat stress risks during heatwave periods, thus in prioritizing high-risk hotspot areas for planning and implementing adaptation solutions through local decision-making processes and planning instruments. To this aim, the risk index calculation could be rescaled at the municipal level to offer proper guidance to local practitioners, supporting them in concentrating policy efforts and investments for promoting adaptation actions in more risky areas (e.g., through retrofitting existing public spaces). On the other hand, at the regional scale, it can be used to support and inform policy and (co-)financing mechanisms for supporting adaptation interventions starting from concerted decision-making processes between the (superordinate) regional and municipal levels. Actually, the FVG Regional Spatial Plan explicitly envisages innovative forms of concerted planning between the regional and the municipal authorities for strategic themes such as the environmental ones through the so-called instrument of 'Territorial Projects'. These are 'the implementation tools of large-scale strategic themes that [...] have the task of transposing and evaluating on a suitable scale the major interventions in a way that will [...] have to foster positive effects on the local level' (Regione Autonoma Friuli Venezia Giulia, n.d.). Forms of preferential concertation between the Region and the municipalities affected by the major risk conditions can therefore be proposed (also) based on the evidence of spatially explicit assessments like the one proposed in this study to inform, guide, and prioritize the (co)financing and implementation of larger-scale interventions that may have tangible positive effects (also) at the local scale, in this case in terms of urban heat stress reduction. For example, the design and implementation of regionally-relevant ecological corridors (i.e., identified in the Regional Landscape Plan) or the proposal of supra-municipal parks (i.e., an instrument established by a regional law) can be fine-tuned in concerted planning processes to (also) maximize the provision of local cooling benefits in the urban areas identified as high-risk hotspots. Or prioritization criteria for accessing regional funding schemes that can be used to finance environmental and climate actions may be defined (also) based on risk hotspot identification.

However, it has to be noted that the proposed risk assessment is not meant to be the sole instrument for basing decisions but should be tailored and critically used by decision-makers together with other types of information and knowledge to reflect on the different factors concurring to determining the final risk condition and to consequently better inform spatial choices toward risk reduction (Kythreotis et al. 2024). For example, weighting/modulating factors can be introduced in the calculation and combination of the risk components (e.g., vulnerability, exposure) and related indicators to assign more/less relative importance to specific factors that local decision-makers want to emphasize or adjust to better reflect local peculiarities. Future research should focus on fine-tuning these practical aspects together with practitioners to test the applicability of the approach in real-world decision-making contexts, as well as on testing the replicability of the method in other regions/cities, also using different data (e.g., future climate scenarios, other socio-demographic characteristics of population, etc.) or integrating/expanding the scope of the assessment (e.g., including non-resident populations – such as workers – as exposure).

Finally, it is worth noting that, while the proposed assessment method is aimed at promoting sustainable planning decisions for people vulnerability/risk reductions, if a high-risk area is characterized by a significant presence of economically disadvantaged population groups, special attention should be paid since, especially in cases of green adaptation interventions that may trigger unwanted gentrification processes (e.g., Camerin & Longato 2024), these population groups may be displaced in other (more) deprived areas if no specific measures to prevent this situation are taken early on in the decision-making process. These could include the adoption of specific housing policies to counteract the likely increase of house prices and protect existing residents from displacement (Derickson et al., 2021). Or the implementation of diffuse green interventions instead of fewer, big green areas, which has been claimed to be more effective and equitable in terms of social impacts, even if this action alone could not always be sufficient if not paired with strong housing policies (e.g., Bockarjova et al., 2020).

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References

Aflaki A., Mirnezhad M., Ghaffaraianhoseini A., Ghaffarianhoseini A., Omrany H., Wang Z.-H. & Akbari H. (2017). Urban heat island mitigation strategies: A state of-the-art review on Kuala Lumpur, Singapore and Hong Kong. *Cities, 62*, 131–145. https://doi.org/10.1016/j.cities.2016.09.003

ARPA FVG (2018). Studio conoscitivo dei cambiamenti climatici e di alcuni loro impatti in Friuli Venezia Giulia. Retrieved from: https://www.arpa.fvg.it/temi/temi/meteo-e-clima/pubblicazioni/studio-conoscitivo-dei-cambiamenti-climatici-e-di-alcuni-loro-impatti-in-friuli-venezia-giulia/

ARPA FVG (2023). Il Clima del Friuli Venezia Giulia. Retrieved from: https://www.osmer.fvg.it/clima/clima_fvg/02_documenti_descrittivi,_report_e_approfondimenti/01_Il_clima_del_Friuli_Venezia_Giulia/clima_fvg-divulgativo.pdf

ARPA FVG (n.d.). Mappe climatiche (raster), sezione Clima FVG. Retrieved from: https://www.meteo.fvg.it/clima.php?ln=

Beltramino, S. et al. (2022). Assessing territorial vulnerability. *TeMA - Journal of Land Use, Mobility and Environment*, 15 (3), 355-375. http://dx.doi.org/10.6092/1970-9870/9069

Bockarjova, M., Botzen, W., Van Schie, M. & Koetse, M. (2020). Property price effects of green interventions in cities: A meta-analysis and implications for gentrification. *Environmental Science & Policy*, 112, 293–304. https://doi.org/10.1016/j.envsci.2020.06.024

Burkhard, B., Kandziora, M., Hou, Y. & Müller, F. (2014). Ecosystem Service Potentials, Flows and Demands – Concepts for Spatial Localisation, Indication and Quantification. *LANDSCAPE ONLINE, 34*, 1-32. DOI 10.3097/LO.201434

Camerin, F. & Longato, D. (2024). Designing healthier cities to improve life quality: unveiling challenges and outcomes in two Spanish cases. *Journal of Urban Design*. https://doi.org/10.1080/13574809.2024.2351925

Ceci, M., Caselli, B. & Zazzi, M. (2023). Soil de-sealing for cities' adaptation to climate change. *TeMA - Journal of Land Use, Mobility and Environment*, 16 (1), 121-145. http://dx.doi.org/10.6093/1970-9870/9395

Derickson, K., Klein, M. & Keeler, B. L. (2021). Reflections on Crafting a Policy Toolkit for Equitable Green Infrastructure. Npj Urban Sustainability, 1(1), 21. https://doi.org/10.1038/s42949-021-00014-0

Ellena, M., Melis, G., Zengarini, N., Di Gangi, E., Ricciardi, G., Mercogliano, P. & Costa, G. (2023). Micro-scale UHI risk assessment on the heat-health nexus within cities by looking at socio-economic factors and built environment characteristics: The Turin case study (Italy). *Urban Climate*, 49, 101514. https://doi.org/10.1016/j.uclim.2023.101514

Geneletti, D., Zardo, L. & Cortinovis, C. (2016). Promoting nature- based solutions for climate adaptation in cities through impact assessment. In: D. Geneletti (ed.), *Handbook on Biodiversity and Ecosystem Services in Impact Assessment*. Edward Elgar Publishing. https://doi.org/10.4337/9781783478996.00025

IPCC (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi:10.1017/9781009325844

Isola, F., Leone, F. & Pittau, R. (2023). Evaluating the urban heat island phenomenon from a spatial planning viewpoint. A systematic review. *TeMAa. Journal of Land Use, Mobility and Environment*, 75-93. http://dx.doi.org/10.6093/1970-9870/10306

Italian Ministry of Health (n.d.). Chi rischia di più, sezione Ondate di Calore. Retrieved from: https://www.salute.gov.it/portale/caldo/dettaglioContenutiCaldo.jsp?lingua=italiano&id=420&area=emergenzaCaldo&menu=vuoto#disagiate

Jibhakate, S. M., Timbadiya, P. V. & Patel, P. L. (2023). Multiparameter flood hazard, socioeconomic vulnerability and flood risk assessment for densely populated coastal city. *Journal of Environmental Management*, 344, 118405. https://doi.org/10.1016/j.jenvman.2023.118405

Kim J., Lee D.-K., Brown R.B., Kim S., Kim J.-H. & Sung S. (2022). The effect of extremely low sky view factor on land surface temperatures in urban residential areas. *Sustainable Cities and Society, 80*, 103799. https://doi.org/10.1016/j.scs.2022.103799

Kythreotis, A.P., Hannaford, M., Howarth, C. & Bosworth, G. (2024). Translating climate risk assessments into more effective adaptation decision-making: The importance of social and political aspects of place-based climate risk. *Environmental Science & Policy, 154*, 103705. https://doi.org/10.1016/j.envsci.2024.103705

Logan, T.M., Zaitchik, B., Guikema, S. & Nisbet, A. (2020). Night and day: The influence and relative importance of urban characteristics on remotely sensed land surface temperature. *Remote Sens. Environ., 247*, 111861. https://doi.org/10.1016/j.rse.2020.111861

Longato D. & Maragno D. (2024). Mapping the vulnerability of urban areas in relation to urban heat island by combining satellite and ecosystem service data: a case study in Udine (Italy). *Contesti. Città, Territori, Progetti, 2*, 128–149. Retrieved from: https://oajournals.fupress.net/index.php/contesti/article/view/14816

Maragno, D., Dalla Fontana, M. & Musco, F. (2020). Mapping Heat Stress Vulnerability and Risk Assessment at the Neighborhood Scale to Drive Urban Adaptation Planning. *Sustainability*, *12* (3), 1056. https://doi.org/10.3390/su12031056

Oke T.R., Mills G., Christen A. & Voogt J.A. (2017). Urban Climates. Cambridge University Press.

Pappalardo, S. E., Zanetti, C. & Todeschi, V. (2023). Mapping urban heat islands and heat-related risk during heat waves from a climate justice perspective: A case study in the municipality of Padua (Italy) for inclusive adaptation policies. *Landscape and Urban Planning*, 238, 104831. https://doi.org/10.1016/j.landurbplan.2023.104831

Park C.Y., Park Y.S., Kim H.G., Yun S.H. & Kim C.-K. (2021). Quantifying and mapping cooling services of multiple ecosystems. *Sustainable Cities and Society, 73*, 103123. https://doi.org/10.1016/j.scs.2021.103123

Regione Autonoma Friuli Venezia Giulia (2013). Piano del Governo del Territorio - Documento Territoriale Strategico Regionale (DTSR). Retrieved from: https://www.regione.fvg.it/rafvg/cms/RAFVG/ambiente-territorio/pianificazione-gestione-territorio/FOGLIA5/

Reiners P., Sobrino J. & Kuenzer C. (2023). Satellite-Derived Land Surface Temperature Dynamics in the Context of Global Change—A Review. *Remote Sensing, 15*, 1857. https://doi.org/10.3390/rs15071857

Rocha, A.D., Vulova, S., Förster, M. et al. (2024). Unprivileged groups are less served by green cooling services in major European urban areas. *Nature Cities, 1*, 424-435. https://doi.org/10.1038/s44284-024-00077-x

Santamouris, M. (2020). Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. *Energy and Buildings, 207*, 109482. https://doi.org/10.1016/j.enbuild.2019.109482

Stiuso, T. (2025). Exploring open and green space characteristics for climate change adaptation: a focus on the urban heat island. *TeMA - Journal of Land Use, Mobility and Environment*, 18 (1), 161-167. http://dx.doi.org/10.6092/1970-9870/11636

Yu Z., Yang G., Zuo S., Jørgensen G., Koga M. & Vejre H. (2020). Critical review on the cooling effect of urban blue-green space: A threshold-size perspective. *Urban Forestry & Urban Greening, 49*, 126630. https://doi.org/10.1016/j.scs.2023.104952

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