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Investigating Social Vulnerability to Extreme Heat: Heat Islands and Climate Shelters in Urban Contexts: The Case of Bologna

Elisa Maccabiani, Munazza Usmani , Riccardo Nanni and Maurizio Napolitano *

Fondazione Bruno Kessler, Digital Commons Lab, Via Sommarive 18, 38123 Trento, Italy;
elisa.maccabiani@unitn.it (E.M.); musmani@fbk.eu (M.U.); rnanni@fbk.eu (R.N.)
* Correspondence: napo@fbk.eu

Abstract: In this article we present three instruments: (1) a social vulnerability to extreme heat index to identify the areas of a city (and populations thereof) more vulnerable to extreme heat due to climate change (heat islands); (2) a new overall fragility index that incorporates social vulnerability to extreme heat as well as socioeconomic indicators; and (3) a climate shelter index (CSI) to identify areas within a city that can provide relief from extreme heat based on green and blue solutions. We elaborated these three indexes to measure social vulnerability to extreme heat in the municipality of Bologna, which serves as this article's case study. By analyzing the connections between social vulnerability to extreme heat and several socio-demographic variables in Bologna, we found that a decrease in income is significantly correlated with an increase in social vulnerability to extreme heat in urban contexts. A comparison between our new overall fragility index and the existing index adopted by the municipality of Bologna (Indice di fragilità, Comune di Bologna) showed that about 75% of the statistical areas observed are worse off when social vulnerability to extreme heat is also considered. Considering social vulnerability to extreme heat shows vulnerabilities in a city (here: Bologna) that the pre-existing index did not consider. These findings and our new indexes can support the Bologna administration (and other local administrations) in addressing the consequences of climate change for their most vulnerable residents.

Keywords: climate shelters; heat islands; urban studies; inequality; climate change

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1. Introduction

Elevated temperatures, especially in urban areas, impact environmental quality and human well-being. Therefore, the need to consider the consequences of heat islands in the context of urban social fragility has emerged: this research addresses climate shelters as instruments to reduce and deal with social vulnerability to extreme heat [1].

This research takes Bologna as a case study. Located in one of Europe's most air-polluted areas (namely, Pianura Padana), Bologna has a high degree of soil consumption in its city center and some of its most working-class neighborhoods [2]. This makes it a significant case study for social vulnerability to extreme heat.

We calculated a social vulnerability to extreme heat indicator by considering several factors: heat islands and cool areas, green or blue nature-based solutions, and the presence of climate shelters. In order to evaluate green areas as possible climate shelters, the climate shelter index (CSI) was created. Analyzing the connections between social vulnerability to extreme heat and several socio-demographic variables, a significant link was found: a decrease in income is significantly correlated with an increase in social vulnerability to extreme heat.

On this ground, we calculated a new overall fragility indicator, including economic, social, demographic, and social vulnerability to extreme heat. This new indicator adds the social vulnerability to extreme heat variable to the existing index adopted by the municipality of Bologna (Indice di fragilità). A comparison between the two indexes shows that about 75% of the statistical areas observed within Bologna are worse off when social vulnerability to extreme heat is also considered. Therefore, taking social vulnerability to extreme heat into consideration shows vulnerabilities in Bologna that the pre-existing index does not consider. Furthermore, it can provide insights into how and where to intervene with climate change adaptation measures.

Altogether, this article presents three new instruments: (1) a social vulnerability to extreme heat index to identify the areas of a city (and populations thereof) more vulnerable to extreme heat due to climate change (heat islands); (2) a new overall fragility index that incorporates social vulnerability to extreme heat as well as socioeconomic indicators; and (3) a climate shelter index (CSI) to identify areas within a city that can provide relief from extreme heat based on green and blue solutions. These instruments were applied to the study of social vulnerability to extreme heat and responses thereto in Bologna.

The next section presents a literature review on urban heat islands. Section 3 discusses our methodological choices. Section 4 showcases the empirical results of this study, while Section 5 discusses their implications. The final section draws conclusions.

2. Literature Review: Urban Heat Islands and Their Policy/Social Implications

Global warming and dramatic changes in climate patterns have impacted the entire world in many aspects of the environment, society, and economy [3]. Previous studies indicate that the global average temperature, both surface and atmospheric, is expected to increase further by the end of this century, with particularly intense effects in urban areas [4]. The Fourth National Climate Assessment, published by the U.S. Global Change Research Program [5], affirms unequivocally that climate change has increased the frequency, duration, and severity of heat waves across the globe, exposing millions of people to heat-related health risks. Indeed, numerous studies show a significant link between rising temperatures and the occurrence of extreme heat events [6]. Furthermore, climate change and heat islands have an important interaction [7]: in many areas of the U.S., there is evidence that the constantly increasing warming trend is intensifying temperatures in heat island areas, which will worsen if there is continuous warming. Changes in land use and land cover influence the climate and weather, contributing to the creation of urban heat islands. The urban heat island (UHI) effect is a heat accumulation phenomenon within urban areas due to urban construction and human activities [8], and it is defined as a temperature difference between urban and rural areas; it is caused specifically by the excess of heat emitted and by the solar gain trapped by the urbanized environment [9]. The UHI effect was found to be related to the urban heat release, properties and structures of the underlying surface, vegetation coverage, population density, and weather conditions [10]. Nowadays, the literature on the UHI effect is very rich and this phenomenon has been studied worldwide: in Italy, there are studies available for some major cities, such as Bologna [11], Milano [12], Firenze [13], Padova [14], and Roma [15].

The scale and intensity of the UHI effect have become increasingly severe and evident due to ongoing urbanization [8]; this, combined with the need to enhance ecological conservation, has led to a new fundamental goal: the realization of sustainable urban development which takes UHIs into account as an important and serious environmental challenge [16].

As urban heat islands and rising temperatures impact our society both socially and economically, important research has been conducted to counterbalance the consequences of these phenomena, leading to the development of efficient climate change adaptation technologies [17]. Therefore, urban planners are now increasingly adopting sustainable solutions to alleviate the excessive thermal stress associated with UHIs [18]. Five main strategies have been identified based on the existing literature and climate shelter definitions formulated by institutional environmental protection bodies such as the US's Environmental Protection Agency:

(1) Trees and vegetation: reducing urban heat through shading and evapotranspiration, improving thermal comfort [19,20];
(2) Green roofs: growing a vegetating layer on a rooftop lowers roof and air temperatures, reducing the cooling load and improving thermal comfort [21,22];
(3) Cool roofs: absorbing and transferring less heat compared to traditional roofs, lowering building interior temperatures and reducing energy consumption [23];
(4) Cool pavements: reducing surface temperatures and limiting heat radiation into the atmosphere, mitigating heat islands [24];
(5) Smart growth: encouraging tree planting and the creation of green spaces, improving the resilience and liveability of communities [7].

A new possible solution, which could be considered as part of the "Trees and vegetation" strategy, was ideated in Barcelona, Spain: the climate shelter. In order to cope with heat waves, Barcelona City Council has decided to create a network of climate shelter spaces [25]. Selected areas in a city, especially green areas, can be converted into climate shelters by implementing changes to enforce specific characteristics: a climate shelter should be easily accessible, free, public, and safe with a green surface area of at least 0.5 hectares and an NDVI (normalized difference vegetation index) of at least 0.4 as defined by the Barcelona for Climate project [25]. Moreover, there should be a rest area with benches, picnic tables, and free water for everyone, so that people can take refuge during heat waves and find refreshment and thermal comfort [26].

This article advances knowledge on climate shelters as a strategy to mitigate the impact of climate change in urban contexts.

3. Materials and Methods

3.1. Study Area

Our study observed an ancient city in the center of Italy: the municipality of Bologna covers a total area of 141 km^2, with a population of nearly 390,000 as of 2023. The territory includes six districts and is divided into 18 zones and 2333 census sections defined by the Istat (Italian National Institute of Statistics) in the general censuses. Furthermore, Bologna is divided into 90 statistical areas: this subdivision responds to the need to define a more fine-grained reading "grid" than the traditional subdivision of Bologna into neighborhoods or zones and that at the same time is more concise than the subdivision into census sections [27].

Bologna is a relevant case study to observe heat effect mitigation strategies in Europe as it is located in one of Europe's most air-polluted areas (that is, Pianura Padana). Furthermore, Bologna has a high population density and reduced greenery in its city center and some of its most working-class neighborhoods, being the core of one of Italy's most important industrial areas [2].

Cities of the Pianura Padana, also known as the River Po Valley, regularly feature among the top 10 European cities by air pollution. Cremona, Vicenza, Padova, Venezia, and Piacenza are five of the ten most air-polluted cities in Europe at the time of writing, and they are all based in the Pianura Padana. Turin, Bergamo, Brescia, Treviso, and Milan are in the top 20 [28]. The reasons for this are the geographical and climatic conditions of the area: humid, non-windy, and shielded by the Alpine arch—a combination that creates the conditions for air pollutants to accumulate. Pollutants are especially produced by the industrial powerhouses of cities such as Milan, Turin, and Bologna [29].

While faring better than other Pianura Padana cities in terms of air pollution [28], Bologna is a good case study due to the conformation of its very urbanized city center and industrial capacity. Furthermore, the local government provides a multitude of systematized open data that facilitate the analysis [30].

3.2. Data

Three main data types were used in this study: socio-demographic indicators, environmental and urban characteristics, and air temperature data.

The socio-demographic data [31] used included age (5 classes to distinguish different age ranges); gender (male or female); citizenship (2 classes: Italian or foreign); and income (average income per contributor). The overall fragility index, obtained from Mappa della Fragilità (Mappa della Fragilità was a study conducted by the municipality of Bologna to map the conditions of fragilities and marginalization of different kinds within its administrative territory and put forward policies to address them [32]), represented further important socio-demographic data for this research, and it was calculated using a weighted average of indicators of potential demographic, social, and economic fragility [33].

Data about environmental and urban characteristics were collected from different sources: in the open data portal of the municipality of Bologna (Open Data Comune di Bologna), one could access data about parking areas reserved for vehicles serving people with disabilities [34], data on bus stops [35], and data about management units [36]. Among the latter, only those categories representing public green spaces enjoyable for free by people were selected, specifically “school green”, “garden”, “park”, “extensive park”, and “sports green”, while excluding “water bodies (ponds, streams, and hillside ditches)”, “car parks”, “green landscaping”, and “green street landscaping”. The DBSN (DataBase di Sintesi Nazionale [37]), a geographic database of the Italian territory, represented another important source of data about watercourses, vegetation, protected natural areas, and agricultural cultivation. Lastly, by using OpenStreetMap, (OpenStreetMap (OSM) is a collaborative project aimed at creating free-content maps of the world) the following data were accessed: drinking fountains, picnic tables, and benches.

Air temperature data at 4 p.m. of June, July, and August 2022 and 2023 were used to identify heat and cold islands. The Italian health authorities recommend people avoid outdoor activities between 1 and 4 p.m. during summer days (this recommendation is expanded to 11 a.m. to 18 p.m. during heat waves) [38]. Therefore, observing 4 p.m. temperature data allowed us to observe the heat island situation at the hottest time of the day in which people resume outdoor activities. Data were satellite-based and provided by Meteoblue. These data covered only some statistical areas of the municipality of Bologna; hence, a selection was made by overlaying the map of the city with the GeoTIFF temperature files: as a consequence, the north and south areas were not included in the current research, as can be seen in Figure 1.

This selection implies the exclusion of some areas that would be interesting to analyze, such as Pilastro and Borgo Panigale. Pilastro was created to meet the great demand for affordable housing following the postwar wave of immigration: low-cost social housing was built, thus giving rise to a working-class district [39,40]. Borgo Panigale is known as an industrial center, where important manufacturing and commercial activities are still present today [41]. Both of these areas of Bologna have faced problems related to urban decay, safety, and quality of life, which is why they would be an interesting study area for this research [42]. Nevertheless, the area covered by Meteoblue data constitutes a representative model of cities characterized by a built-up historic center with a limited presence of vegetation.

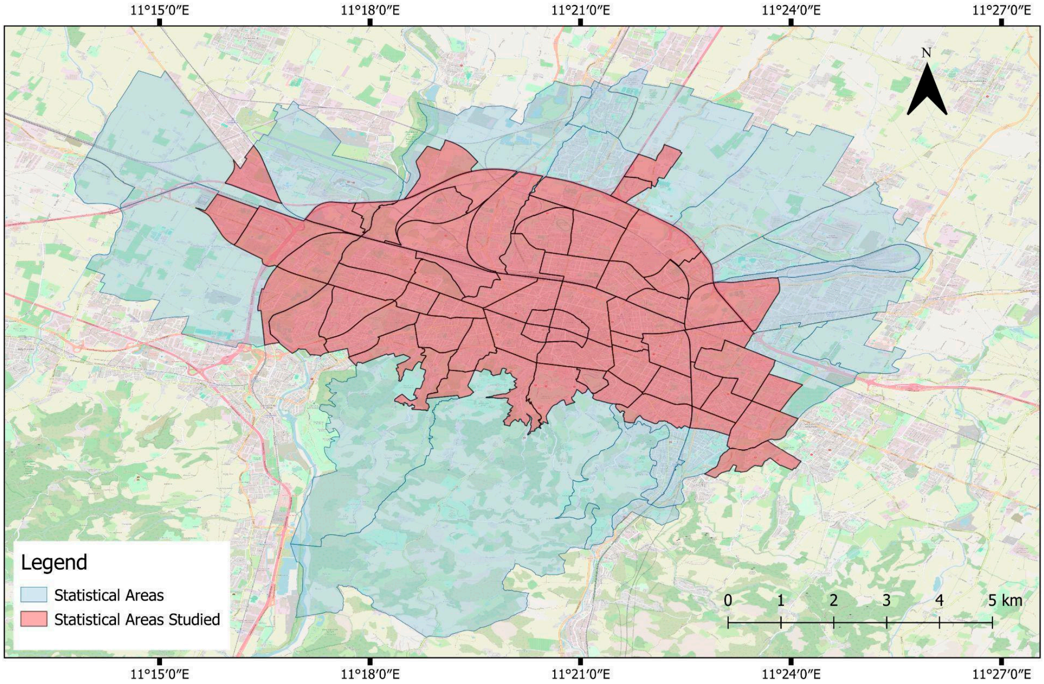
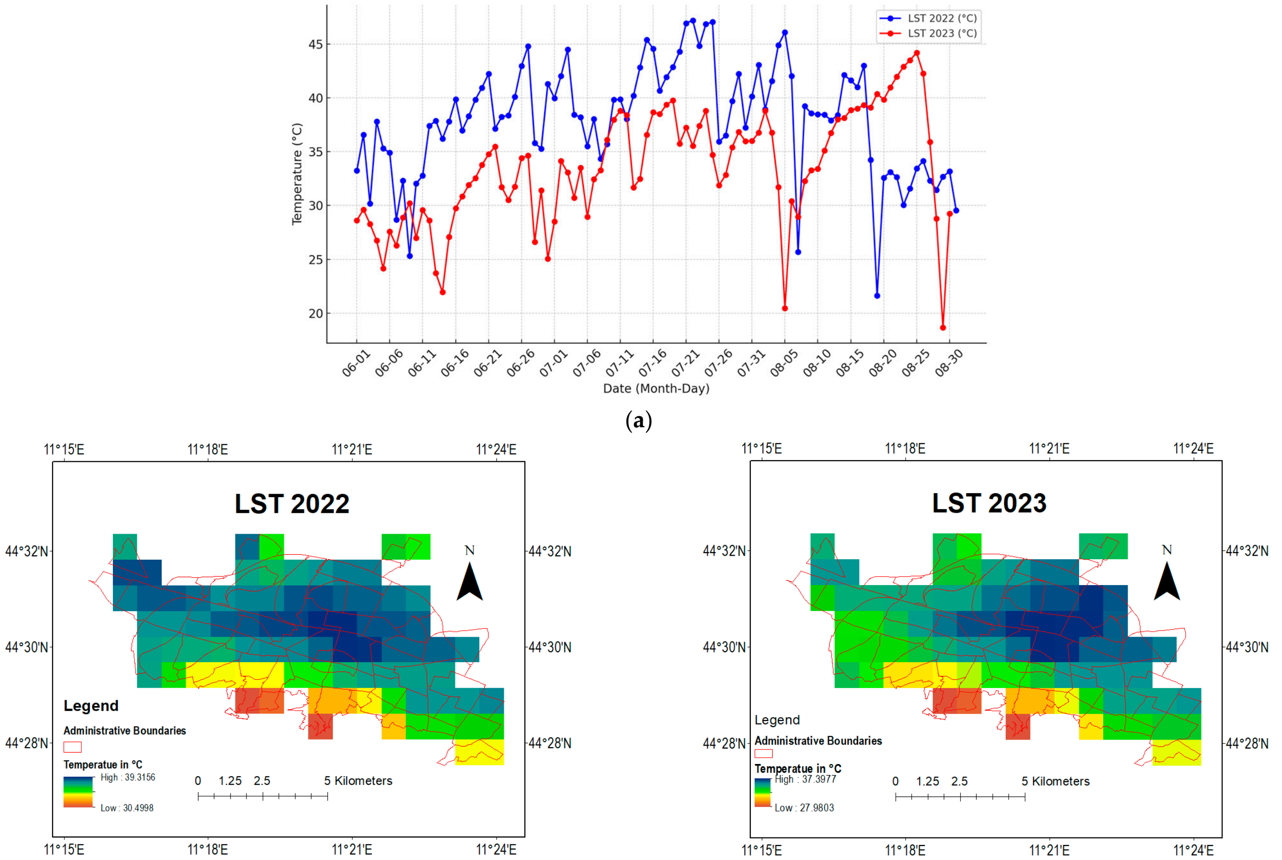


Figure 1. Representation of the 90 statistical areas in the municipality of Bologna. In red are the areas considered for this research.

An alternative instrument for this analysis could be NASA's Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), which records the ground surface temperature. This source is free, easily accessible, and collects images of the entire world, but, on the other hand, there are some limitations: the measurements of temperature are not made every day at the same hour; indeed, they are usually made at different moments of the day or night and occasionally some days may be completely skipped, thus creating a lack of data. For the purpose of this research, it would be best to compare air temperatures measured at the same time to maintain the same environmental conditions and limit possible bias. Another aspect that should be considered is that the ECOSTRESS acquires data with pixel dimensions of approximately 69.997, −69.997, whereas Meteoblue provides a better defined resolution as pixels have a size of around 1.258×10^{-4}, -8.982×10^{-5}. The spatial resolution represents a key factor in this study: having more precise data allows heat islands to be identified more accurately, ruling out possible wrong generalizations.

We also ran a land surface temperature (LST) investigation to further validate the air temperature analysis. The spatial distribution and temporal trends of the LST during the two years are depicted in Figure 2. The graph, which shows daily temperature changes, shows a general tendency of higher temperatures in 2023 compared to 2022, especially in late July and early August. At 4:00 p.m., these temperature peaks depict notable heat waves or events that have affected the area, reflecting the situation of the heat island during the day. In order to obtain the LST at 4:00 p.m. for the summer months of 2022 and 2023 in Bologna, Italy, we used Meteosat SEVIRI data, which are satellite-based and give LST measurements with a spatial resolution of roughly 3 km. The data are accessible every 15 min.



(b) (c)

Figure 2. (**a**) LST time series at 4:00 pm for the study area in Bologna, Italy, during June, July, and August in 2022 (blue) and 2023 (red), showing daily temperature variations. (**b**,**c**) LST spatial maps for the same period in 2022 and 2023.

To ensure consistency across all datasets, the spatial resolution of the Meteoblue temperature data was aligned with the predefined statistical areas used for socio-demographic indicators and urban characteristics. For temporal alignment, temperature data were extracted or averaged for the relevant study periods, ensuring coherence between the socio-demographic indicators, which were static, and the dynamic environmental data.

3.3. Methods

This study evaluated multiple aspects of social vulnerability to extreme heat through spatial and statistical methods. It aimed to assess the efficiency of green spaces as possible climate shelters and subsequently identify not only the hottest areas of the city but also the most climatically fragile. Furthermore, it explored possible relationships between social vulnerability to extreme heat and socio-demographic factors.

First, the CSI was defined, assigning a value from 0 to 1 (where 0 indicates a bad climate shelter and 1 a perfect climate shelter) to all green areas in a city. The CSI refers only to outdoor climate shelters, so it considers only the following aspects of an area to calculate the score:

1. It should be public and free, in order to ensure access for everyone;
2. It should have a green surface area > 0.5 hectares [25];
3. It should have an NDVI index > 0.4 [25];

4. It should be easily accessible: in particular, people should be able to reach it via a bicycle/footpath, there should be at least one bus stop within a 5 min walking distance, and it should be accessible for people with reduced mobility [25,26];
5. It should have at least one drinking fountain to ensure access to free water for everyone [26];
6. It should have a rest area with benches or picnic tables [26].

The Unità Gestionali dataset of the municipality of Bologna [36] was used to identify public green spaces and calculate the green area in square meters and hectares, guaranteeing that accessibility was free of charge for everyone, as required in point 1. For calculating the CSI, the *NDVI* is another key concept, which is derived from satellite imagery and calculated with the formula

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

where *NIR* is the light reflected in the near-infrared spectrum and *RED* is the light reflected in the red range of the spectrum (Observatory, 2000). A GeoTIFF of the *NDVI* in Bologna was created (to calculate the *NDVI* in Python, instructions are available from Planet [43]). Using this file, it was possible to calculate the average NDVI for each green area in the municipality of Bologna and hence subsequently verify which green areas satisfied the criterion provided by the CSI.

Point 4 of the CSI states that a good climate shelter should be easily accessible. In previous research [44], different modes of transport (walking, cycling, bus, and car) were considered to study accessibility. Therefore, in order to assess accessibility, which is commonly defined as the ease of reaching a destination [45], several factors were considered: the identification of entrances to green areas, the calculation of 5 and 10 min isochrones to understand what was nearby, the location of bus stops within a 5 and 10 min walk, and disabled parking spaces [34] near the park entrances. After acquiring all the previously mentioned elements, an accessibility index was developed for each green area considering the following aspects: accessibility via pedestrian pathways; accessibility via bicycle paths; proximity to bus stops; and the availability of disabled parking. Weights were assigned to these aspects based on empirical and theoretical considerations to reflect their relative importance in determining the overall accessibility. Specifically, footpaths and bicycle lanes were given the highest weights (0.3) as a prior study [46] showed that green space stimulates walking and cycling, as well as being an accessible way of getting around for most people. Previous definitions of bus stops as indicators of the transport conditions and accessibility of a region [47,48], and as point of interest data for representing the spatial accessibility of urban green spaces [49], led us to assign a weight of 0.2 for bus stops within a 5-minute walk, as they were closer, and 0.1 for a 10 min walk. Lastly, since guaranteeing access to green spaces for all, including people with disabilities, is one of the objectives for making cities inclusive, safe, resilient, and sustainable [50], disabled parking spaces were assigned a weight of 0.1. The values of each aspect were normalized and multiplied by their respective weights; the sum of these weighted values resulted in the total accessibility index, which ranged from 0, poor accessibility, to 1, excellent accessibility.

The structures in a green area also play a key role in a climate shelter (see points 5 and 6 above), and therefore all fountains, benches, and picnic tables in the municipality of Bologna were identified using OpenStreetMap.

The variables just mentioned were counted and normalized using min–max normalization; that is, the minimum value was transformed into 0 while the maximum value was transformed into 1. All the others were then transformed proportionally. The surface area and NDVI values were normalized according to predefined thresholds, assigning a value of 0 in the case that the area was less than 0.5 hectares or the NDVI did not exceed 0.4.

The *CSI* was calculated for each green area by combining the normalized variables and their respective weights:

$$CSI = SA \times 0.12 + NDVI \times 0.04 + A \times 0.09 + DF \times 0.27 + B \times 0.27 + PT \times 0.21$$

where the weights are 0.12 for the surface area (*SA*), 0.04 for the NDVI, 0.09 for accessibility (*A*), 0.27 for drinking fountains (*DF*s), 0.27 for benches (*B*s), and 0.21 for picnic tables (*PT*s). Principal component analysis (PCA)[4] was used to determine the weights of each CSI component, as it is a statistical method that identifies the underlying components driving variation in a dataset. The values obtained with the CSI provided a quantitative measure of each location's suitability as a climate shelter, considering the combination of physical attributes and services previously studied.

To understand climate conditions in the municipality of Bologna, an indicator for situations of potential social vulnerability to extreme heat was defined considering the following aspects for each statistical area:

1. The percentage of the surface occupied by heat or cold islands;
2. The percentage of the surface covered by nature-based green solutions (public and private parks, gardens, urban greenery, etc.);
3. The percentage of the surface covered by nature-based blue solutions (rivers, ponds, falls, etc.);
4. The average of the CSI for each statistical area considered.

Identifying heat and cold islands was possible with the Meteoblue air temperature data from June, July, and August 2022 and 2023. For each day in this timeframe, a satellite image was taken at 4 p.m., and they were used to find hot and cold spots. Specifically, each GeoTIFF was read as a NumPy array (considering that the temperature is stored in the first band of the file), and thereafter quartiles (Q1, Q2, Q3, and Q4) were calculated for non-zero temperature values. Values belonging to Q1 were considered cold islands while values in Q4 were heat islands; on the other hand, Q2 and Q3 were not classified as either hot spots or cold spots. To determine whether a cell actually represented a hot zone, cell positions were counted within each quartile: if a cell occurred more than 92 times (at least half of the total days) in the same quartile, it could be considered a significant hot or cold spot; otherwise, it was not significant. The result was a GeoTIFF in which each cell was marked 0 if it did not belong to the same quartile a considerable number of times or 1, 2, 3, and 4, which correspond to Q1, Q2, Q3, and Q4 (Figure 3). Areas labeled with the number 4 represent hot spots in the municipality of Bologna, while those with the number 1 are cold spots. In the end, raster data were converted into vector data: this process created polygons from the raster data based on pixel values, aggregating pixels with the same values (PCA was used to determine the weights of each CSI component as suggested here: % Performing principal component analysis (PCA) to determine weights for index indicators).

Nature-based solutions can help mitigate impacts due to climate change and serve as proactive adaptation solutions for municipalities [51]. For this reason, nature-based green and blue solutions were identified in the studied area. Using QGIS, nature-based green solutions were unified in a single layer, including all vegetation data; the same approach was performed for blue solutions, representing all types of watercourses. This analysis made it possible to identify green and water areas and calculate each statistical area's percentage coverage. With the following formula, the indicator of potential social vulnerability to extreme heat was calculated (social vulnerability to extreme heat is indicated as HF (short for "heat fragility")):

$$HF = 1 - (G + B + CSI + C - H)$$

where G and B are the percentages of green and blue surfaces, the CSI is obtained by calculating the average of the scores of the climate refugees eventually present in the statistical area, C is the percentage of the area with a cold surface temperature, and H is the percentage of the area that was classified as a hot spot. In this formula, two groups of indicators can be distinguished: G, B, CSI, and C are indicators of benefit, which means that high values of these aspects can contribute to reducing social vulnerability to extreme heat and therefore make the area less vulnerable; on the other hand, H represents an indicator of damage, since a high value of it will contribute to an increase in social vulnerability to extreme heat. The index is calculated by finding the difference between the sum of the benefit factors and the damage. This result is subtracted from 1 to invert the contribution of the indicators, whereby high values of G, B, CSI, and C reduce the index, while high values of H increase the index. Both the absolute index and the normalized index were calculated for the social vulnerability to extreme heat indicator to provide an absolute and a relative measure of the phenomenon.

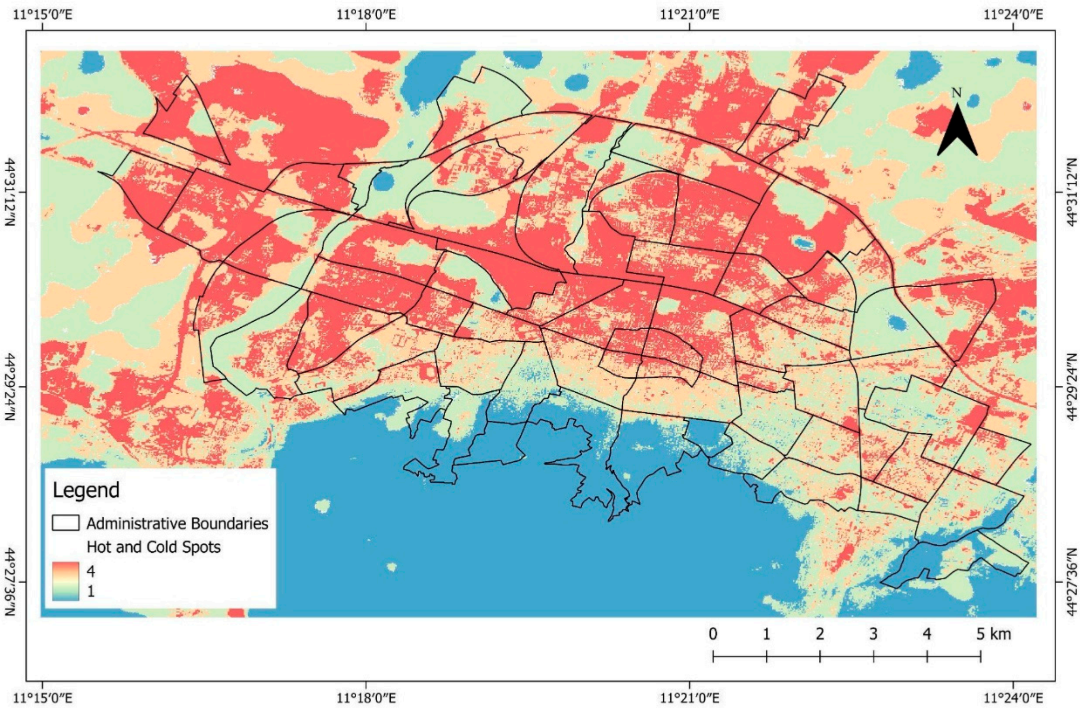


Figure 3. GeoTIFF of urban hot and cold spots in the municipality of Bologna.

In order to define the level of fragility of the statistical areas under consideration, social, demographic, and economic aspects were taken into account while also including social vulnerability to extreme heat. Before performing the calculations, min–max normalization was applied to all indicators, resulting in values with a range from 0 to 1. Afterward, the calculation of the new indicator of overall potential fragility was performed using a weighted average of the 4 indicators, economic (EF), social (SF), demographic (DF), and social vulnerability to extreme heat (HF):

$$F = EF \times 2.25 + SF \times 3.25 + DF \times 2.25 + HF \times 2.25$$

As in the original study on the fragility map in Bologna [52], a higher weight was maintained for social fragility by giving it 3.25, while the other indicators have a weight of 2.25.

Since some studies have shown that groups with a limited adaptive capacity, including low-income and/or non-white people, are more at risk of heat exposure [53,54] and thus may be subject to climate injustice, it was interesting to investigate a possible relationship between social vulnerability to extreme heat and certain socio-demographic factors. Income, citizenship, age, and gender were the variables that were considered in order to comprehend whether social vulnerability to extreme heat occurs in conjunction with specific features. A multiple linear regression analysis was conducted to understand the relationship between the level of social vulnerability to extreme heat, which was the dependent variable, and a set of socio-demographic predictor variables, namely the average income, age (with many categories: 0–14, 15–29, 30–44, 45–64, and over 65), gender (male or female), and citizenship (Italian or foreign).

4. Results

The results have been divided into three sections. This section begins by providing an overview of the CSI and its results in the municipality of Bologna. This is followed by the results of the statistical analysis, which identify relationships between social vulnerability to extreme heat and specific socio-demographic groups. Finally, it identifies the influence of social vulnerability to extreme heat on the overall fragility level.

4.1. Climate Shelter Index

The CSI constitutes an evaluation indicator for green areas, assessing their potential as climate shelters by assigning them a value between zero and one, where zero indicates a location that citizens can hardly use as a climate shelter, while one represents the optimal climate shelter. In the municipality of Bologna, the area investigated had 727 public and free green spaces, of which 181 had a green area larger than 0.5 hectares and an NDVI level greater than 0.4, thereby meeting the climate shelter requirements. By also considering for each green area the accessibility and the presence of drinking fountains, benches, and picnic tables, it was found that the top five parks with a higher CSI (Table 1) were Parco della Montagnola, with a CSI of 0.933; Giardino Centro Civico San Donato (Ex Bentivogli E Marcinelle), with a CSI of 0.861; Parco Nicholas Green (Ex Villa Contri), with a CSI of 0.717; Parco Di Villa Angeletti, with a CSI of 0.712; and Parco Lunetta Gamberini, with a CSI of 0.692. The first three parks had all the features necessary for a good climate shelter, whereas in the following parks, there were some missing features, for example, picnic tables, which are necessary to create a rest area for people, or drinking fountains, which are essential to provide access to drinking water for everyone. All the appropriate structures and services must be in place to ensure that a green area becomes a good climate refuge.

Table 1. The 5 green areas with the highest CSI.

Name	Area (Ha)	Drinking Fountains	Picnic Table	Benches	NDVI	Access Index	CSI
Parco Della Montagnola	2.84	yes	yes	yes	0.72	0.63	0.93
Giardino Centro Civico San Donato	0.94	yes	yes	yes	0.65	0.20	0.86
Parco Nicholas Green (Ex Villa Contri)	5.05	yes	yes	yes	0.68	0.26	0.72
Parco di Villa Angeletti	5.95	yes	no	yes	0.77	0.23	0.71
Parco Lunetta Gamberini	6.43	yes	no	yes	0.67	0.44	0.69

4.2. Social Vulnerability to Extreme Heat

The social vulnerability to extreme heat indicator enables the understanding and quantification of the fragility degree in relation to climate problems, providing a comprehensive and detailed picture of the resilience of each statistical area when facing environmental and climate pressures. The relative index of social vulnerability to extreme heat goes from zero to one, and it is classified into five different categories: 0–0.2 corresponds to low social vulnerability to extreme heat, 0.2–0.4 is moderate, 0.4–0.6 is medium, 0.6–0.8 is high, and 0.8–1 is very high (Figure 4).

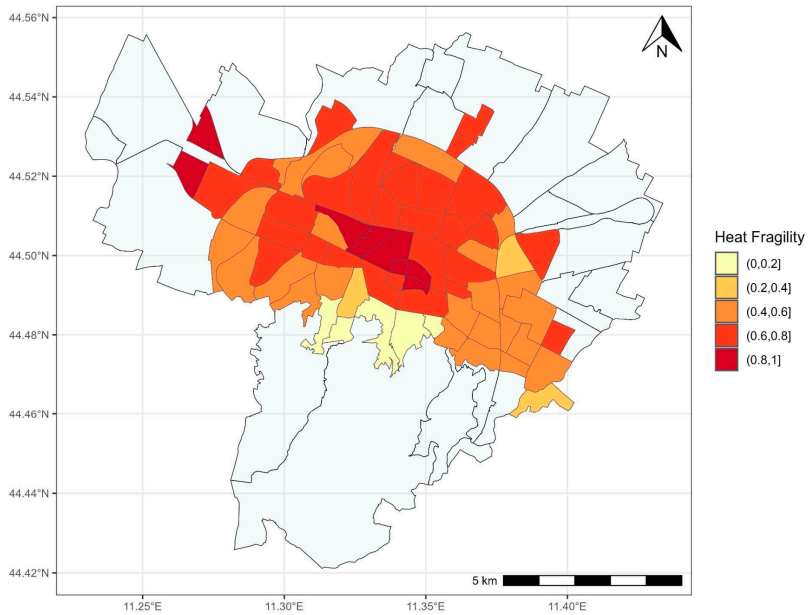


Figure 4. Visual representation of the indicator of social vulnerability to extreme heat (normalized index).

Most statistical areas had a medium or high level of social vulnerability to extreme heat. Specifically, 28 zones out of 68 showed a high CSI score, and 24 areas had a medium level; furthermore, among the remaining statistical areas, 8 exhibited a very high level, 5 showed a low level, and 3 had a moderate level. Observing the results, it emerged that the presence of heat islands in a statistical area greatly influences social vulnerability to extreme heat since it raises its value; on the other hand, an important aspect that performs the opposite effect by reducing social vulnerability to extreme heat is the percentage of green space.

Analyzing the output of the multiple linear regression analysis, we can observe a meaningful relationship: the average income shows a significant negative correlation with social vulnerability to extreme heat. In particular, the estimated value of -9.929×10^{-6} suggests that, on average, a decrease of one unit in the average income is associated with an estimated increase of approximately 9.929×10^{-6} in the social vulnerability to extreme heat index, meaning that an increase in the income is associated with a decrease in social vulnerability to extreme heat; moreover, this coefficient is statistically relevant because of the small p-value (0.0000657). This result suggests that low-income people and families are more likely to suffer from higher social vulnerability to extreme heat, as they are more likely to live in areas with a greater presence of heat islands. This hypothesis is supported by previous research indicating a consistent statistical association between lower socioeconomic conditions and a greater urban heat risk [53]. The problem is documented in the literature as thermal inequity, which is a climate gap typically defined as the disparity in the vulnerability of racial/ethnic minorities and people with lower social and economic status to the adverse consequences of climate change in urban areas [55]. Furthermore, previous research in the area of Bologna showed that foreign citizens live mainly in the working-class areas and poorer suburbs of the city [56]; hence, it is possible to assume that non-Italian individuals, living in lower income areas, are also more affected by social vulnerability to extreme heat. The fact that a significant part of the variance in social vulnerability to extreme heat can be explained by income could represent a starting point for identifying potential predictors of vulnerabilities in statistical areas.

4.3. Overall Fragility

In the context of fragility assessment, the new overall indicator takes a comprehensive approach, including not only social, economic, and demographic spheres but also social vulnerability to extreme heat, which could undermine the resilience of an area. Some observations can be made: according to the new indicator of overall fragility, with values from 0 to 1, there was one statistical area with a low level of fragility (0, 0.2], then there were six moderate areas (0.2, 0.4], forty-two medium areas (0.4, 0.6], nine high areas (0.6, 0.8], and only one very high area (0.8, 1]. About 75% of the areas were thus found to be worse off than expected under the previously existing index after the inclusion of social vulnerability to extreme heat (Figure 5). This result raises questions about the impact that environmental and climate problems can create in cities. The level of overall fragility decreased in only 13 statistical areas. These outcomes suggest that statistical areas are vulnerable to climate problems; for this reason, integrating a social vulnerability to extreme heat assessment is essential in order to have a comprehensive perspective of the situations in various areas of the city.

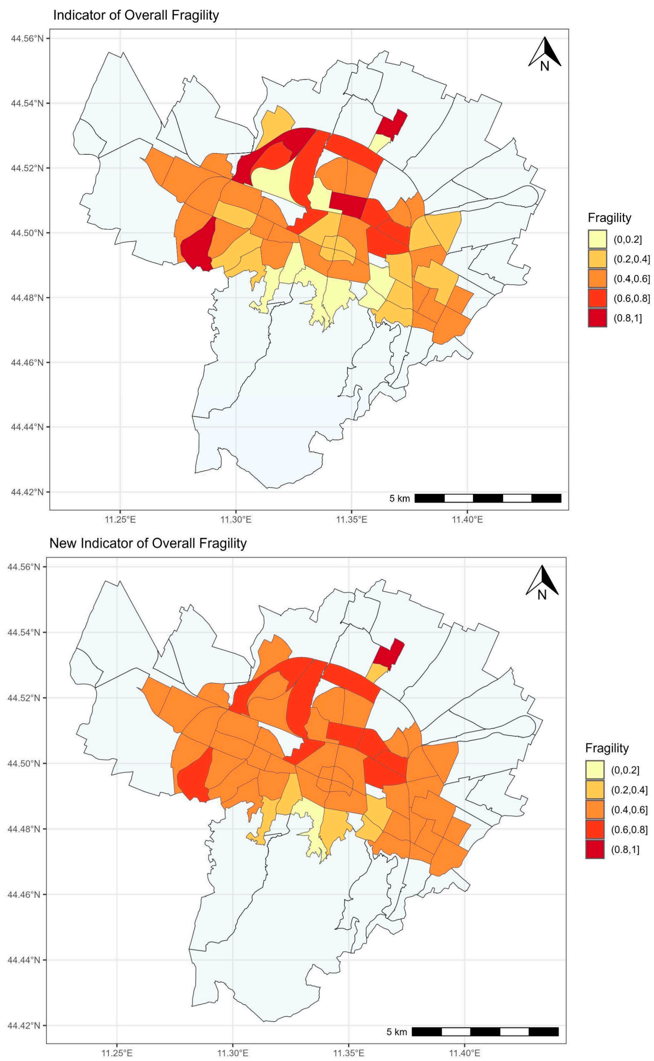


Figure 5. Comparison between the indicator of overall fragility calculated by the municipality of Bologna, considering economic, social, and demographic fragility, and the new indicator of overall fragility, calculated also considering social vulnerability to extreme heat. Both indices are normalized.

5. Discussion

This study examined a series of aspects to achieving an accurate understanding of the causes, consequences, and possible solutions for social vulnerability to extreme heat applied to the municipality of Bologna.

First and foremost, the development of the CSI has proven to be a valuable tool for assessing the effectiveness of green areas as climate shelters. This index is a significant methodological contribution because, by providing the necessary data, it can be applied to any city. It allows for an assessment of the suitability of green areas but at the same time offers a source of inspiration for possible improvements, identifying any lack of facilities or services in a given green space. The adoption of the CSI could be a useful resource for local governments as well, providing both a view of the quality of possible climate shelters and a starting point to identify intervention priorities and guide resource allocation to improve the quality of green spaces available for the community.

This study excluded the northern and southern parts of Bologna from its analysis due to the lack of data on air temperatures in these areas. For this reason, the results can be considered more representative of a built-up historical center than of a municipality. However, the identification of heat islands in the considered region allowed for the visualization of the critical spot during the hottest months. This element, combined with the dCSI and the mapping of green and blue areas, enabled the creation of the indicator of potential social vulnerability to extreme heat. Its contribution is another relevant aspect, as it could help prioritize possible interventions for managing and mitigating climate vulnerabilities. Moreover, a relationship emerged between income and social vulnerability to extreme heat (estimated value = -9.929×10^{-6}; p-value = 0.0000657), showing that a decrease in income is associated with an increase in social vulnerability to extreme heat. This result supports the hypothesis that people with a low income are more susceptible to social vulnerability to extreme heat; hence, the need for specific interventions in economically challenged areas arises to ensure an equitable and targeted approach in addressing social vulnerability to extreme heat and limiting the climate gap.

The integration of social vulnerability to extreme heat into a new overall fragility index revealed a significant impact: when observing the overall fragility of the population after the inclusion of social vulnerability to extreme heat, it was found that about 75% of the statistical areas showed increased fragility. This highlights the fundamental importance of social vulnerability to extreme heat for the definition of fragility as an overall concept.

The results obtained represent a significant starting point in the attempt to analyze the fragilities and challenges that characterize the city studied. These findings help to map the critical issues and vulnerabilities present in the urban context, especially the infrastructural and environmental gaps that require priority attention. Such an analysis offers the opportunity to embark on a path that not only highlights weaknesses but also aims to outline targeted strategies and interventions to improve the situation.

One major drawback to the analysis in this study concerns the availability of temperature data, which do not comprehensively cover all areas in the municipality; in fact, only 68 statistical areas out of 90 were studied. The absence of data on some specific areas affected the completeness of the climate analysis conducted in this research. Another potential risk was an autocorrelation between the variables in the multiple linear regression. Nevertheless, an analysis of the residuals revealed a uniform distribution around the y = 0 reference line, showing no distinct patterns. This suggests that there was no autocorrelation between the observations and confirms the robustness and reliability of the model in explaining the relationship among the variables considered.

Future areas of study should focus on acquiring data encompassing the entire Bologna municipality to obtain a more comprehensive picture and improve the understanding of the relationship between socio-demographic factors and social vulnerability to extreme heat. Furthermore, future studies could consider a larger dataset with temperature data from different times of the year or even run comparisons across cities. Concerning land surface temperature data, new sources such as the ECOSTRESS or Copernicus could be considered in the future. In addition, further research could examine in detail how gender and citizenship/origin influence social vulnerability to extreme heat. Women and foreigners, often with lower incomes, constitute a more fragile part of the population; therefore, it would be valuable to explore this topic further to verify whether gender and citizenship are also significant factors in increasing climate vulnerability. Finally, this study adopted a weak definition of accessibility for people with disabilities. Future studies could use satellite imagery to identify architectural barriers or qualitative observations to assess climate shelters' accessibility.

Despite these limits, this study provides a useful initial understanding of the urban climate island problem in Bologna and a re-discussion of the fragility index including social vulnerability to extreme heat as a metric, while also providing metrics to identify climate shelters. Information on climate shelters and heat islands should be diffused within the city in several languages and formats (online or print) so as to help the population during particularly hot periods. It is also recommended that government agencies make efforts to disseminate information and improve green spaces such as climate shelters. While the current fragility index focuses on socio-demographic and environmental factors, it is important to note that vulnerability and resilience can be enhanced through policy interventions and investments in urban infrastructure, such as parks, water fountains, and improved accessibility. Although this specific study concerns Bologna, the assessment of green areas and the development of interventions to reduce social vulnerability to extreme heat is a good practice for all cities.

6. Conclusions

This study provides compelling evidence that social vulnerability to extreme heat is a problem in urban centers and negatively affects an area's overall fragility. Social vulnerability to extreme heat is associated with a low income and the most deprived people therefore live in more fragile situations: it is crucial that local governments recognize and address these issues to improve living conditions in urban areas.

Climate shelters are a starting point and the first solution to social vulnerability to extreme heat: providing the necessary services and facilities to turn the city's green areas into cool places can make a difference for citizens and tourists, especially during heat waves. To be sure, this study was focused on a single city and considered one specific data source (Meteoblue). Furthermore, data were taken for one single time (4:00 p.m.) of a summer day. Future studies could focus on a larger dataset, run comparisons across cities, or fine-tune the existing instruments.

Nonetheless, the present study found results that are likely transferable to middle-sized cities with climate characteristics similar to Bologna, especially across southern Europe. Furthermore, this study provides an important first step in mainstreaming social vulnerability to extreme heat into general fragility-related policy discussions in urban planning. Through the elaboration of the climate shelter index and the new overall fragility index (which includes social vulnerability to extreme heat), this article provides urban planners and policymakers with useful tools to address climate change effects in a city by identifying and intervening in climate shelters.

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formal analysis and supervision. All authors have read and agreed to the published version of the manuscript.

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References

1. Rocha, A.D.; Vulova, S.; Förster, M.; Gioli, B.; Matthews, B.; Helfter, C.; Meier, F.; Steeneveld, G.-J.; Barlow, J.F.; Järvi, L.; et al. Unprivileged Groups Are Less Served by Green Cooling Services in Major European Urban Areas. *Nat. Cities* **2024**, *1*, 424–435. [CrossRef]
2. European Environment Agency Europe's Air Quality Status 2023. Available online: https://www.eea.europa.eu/publications/europes-air-quality-status-2023 (accessed on 7 May 2024).
3. Abbass, K.; Qasim, M.Z.; Song, H.; Murshed, M.; Mahmood, H.; Younis, I. A Review of the Global Climate Change Impacts, Adaptation, and Sustainable Mitigation Measures. *Environ. Sci. Pollut. Res.* **2022**, *29*, 42539–42559. [CrossRef] [PubMed]
4. Keynyn Brysse, M.O. Naomi Oreskes, Jessica O'Reilly Climate Change Prediction: Erring on the Side of Least Drama? *Glob. Environ. Chang.* **2013**, *23*, 327–337. [CrossRef]
5. USGCRP Fourth National Climate Assessment, Volume II: Impacts, Risks, and Adaptation in the United States. Available online: https://nca2018.globalchange.gov/ (accessed on 1 September 2023).
6. Coumou, D.; Rahmstorf, S. A Decade of Weather Extremes. *Nat. Clim. Chang.* **2012**, *2*, 491–496. [CrossRef]
7. Environmental Protection Agency Heat Island Impacts 2023. Available online: https://www.epa.gov/heatislands/heat-island-trends (accessed on 30 October 2023).
8. Yang, L.; Qian, F.; Song, D.-X.; Zheng, K.-J. Research on Urban Heat-Island Effect. *Procedia Eng.* **2016**, *169*, 11–18. [CrossRef]
9. Centro Euro-Mediterraneo sui Cambiamenti Climatici A Detailed Map of Urban Heat Islands 2023. Available online: https://www.cmcc.it/article/a-detailed-map-of-urban-heat-islands (accessed on 30 October 2023).
10. Rizwan, A.M.; Dennis, L.Y.C.; Liu, C. A Review on the Generation, Determination and Mitigation of Urban Heat Island. *J. Environ. Sci.* **2008**, *20*, 120–128. [CrossRef]
11. Ventura, F.; Gaspari, N.; Piana, S.; Rossi Pisa, P. Evolution of the Urban Heat Island of the City of Bologna (Italy) in the Last 30 Years 2010, 8353. Available online: https://ui.adsabs.harvard.edu/abs/2010EGUGA..12.8353V/abstract (accessed on 30 October 2023).
12. Previati, A.; Epting, J.; Crosta, G.B. The Subsurface Urban Heat Island in Milan (Italy)—A Modeling Approach Covering Present and Future Thermal Effects on Groundwater Regimes. *Sci. Total Environ.* **2022**, *810*, 152119. [CrossRef]
13. Petralli, M.; Prokopp, A.; Morabito, M.; Bartolini, G.; Torrigiani, T.; Orlandini, S. Ruolo Delle Aree Verdi Nella Mitigazione Dell'isola Di Calore Urbana: Uno Studio Nella Città Di Firenze" (‘"The Role of Green Areas in UHI Mitigation: A Study in the City of Florence"’, in Italian). *Riv. Ital. Di Agrometeorol.* **2009**, *1*, 51–58.
14. Noro, M.; Lazzarin, R. Urban Heat Island in Padua, Italy: Simulation Analysis and Mitigation Strategies. *Urban Clim.* **2015**, *14*, 187–196. [CrossRef]
15. Fabrizi, R.; Bonafoni, S.; Biondi, R. Satellite and Ground-Based Sensors for the Urban Heat Island Analysis in the City of Rome. *Remote Sens.* **2010**, *2*, 1400–1415. [CrossRef]
16. Liu, Y.; Wang, Z. Research Progress and Hotspot Analysis of Urban Heat Island Effects Based on Cite Space Analysis. *Land* **2023**, *12*, 1154. [CrossRef]
17. Akbari, H.; Cartalis, C.; Kolokotsa, D.; Muscio, A.; Pisello, A.L.; Rossi, F.; Santamouris, M.; Synnef, A.; Wong, N.H.; Zinzi, M. Local Climate Change and Urban Heat Island Mitigation Techniques—The State of the Art. *J. Civ. Eng. Manag.* **2015**, *22*, 1–16. [CrossRef]

18. Aflaki, A.; Mirnezhad, M.; Ghaffarianhoseini, A.; Ghaffarianhoseini, A.; Omrany, H.; Wang, Z.-H.; Akbari, H. Urban Heat Island Mitigation Strategies: A State-of-the-Art Review on Kuala Lumpur, Singapore and Hong Kong. *Cities* **2017**, *62*, 131–145. [CrossRef]
19. Wang, X.H. Urban Planning Design and Sustainable Development of Forest Based on Heat Island Effect. *Appl. Ecol. Environ. Res.* **2019**, *17*, 9121–9129. [CrossRef]
20. Knight, T.; Price, S.; Bowler, D.; Hookway, A.; King, S.; Konno, K.; Richter, R.L. How Effective Is 'Greening' of Urban Areas in Reducing Human Exposure to Ground-Level Ozone Concentrations, UV Exposure and the 'Urban Heat Island Effect'? An Updated Systematic Review. *Environ. Evid.* **2021**, *10*, 12. [CrossRef]
21. Sailor, D.J.; Elley, T.B.; Gibson, M. Exploring the Building Energy Impacts of Green Roof Design Decisions—A Modeling Study of Buildings in Four Distinct Climates. *J. Build. Phys.* **2012**, *35*, 372–391. [CrossRef]
22. Mihalakakou, G.; Souliotis, M.; Papadaki, M.; Menounou, P.; Dimopoulos, P.; Kolokotsa, D.; Paravantis, J.A.; Tsangrassoulis, A.; Panaras, G.; Giannakopoulos, E.; et al. Green Roofs as a Nature-Based Solution for Improving Urban Sustainability: Progress and Perspectives. *Renew. Sustain. Energy Rev.* **2023**, *180*, 113306. [CrossRef]
23. Ashtari, B.; Yeganeh, M.; Bemanian, M.; Vojdani Fakhr, B. A Conceptual Review of the Potential of Cool Roofs as an Effective Passive Solar Technique: Elaboration of Benefits and Drawbacks. *Front. Energy Res.* **2021**, *9*, 738182. [CrossRef]
24. Kappou, S.; Souliotis, M.; Papaefthimiou, S.; Panaras, G.; Paravantis, J.A.; Michalena, E.; Hills, J.M.; Vouros, A.P.; Ntymenou, A.; Mihalakakou, G. Cool Pavements: State of the Art and New Technologies. *Sustainability* **2022**, *14*, 5159. [CrossRef]
25. Barcelona for Climate—Urban Planning, Ecological Transition, Urban Services and Housing Climate Shelters Network. Available online: https://www.barcelona.cat/barcelona-pel-clima/en (accessed on 30 December 2024).
26. Amorim-Maia, A.T.; Anguelovski, I.; Connolly, J.; Chu, E. Seeking Refuge? The Potential of Urban Climate Shelters to Address Intersecting Vulnerabilities. *Landsc. Urban Plan.* **2023**, *238*, 104836. [CrossRef]
27. Comune di Bologna Redditi per Area Statistica. *Open Data Comune di Bologna*. 2023. Available online: https://opendata.comune.bologna.it/explore/dataset/redditi-per-area-statistica/information/ (accessed on 30 October 2023).
28. European Environment Agency European City Air Quality Viewer. Available online: https://www.eea.europa.eu/en/topics/in-depth/air-pollution/european-city-air-quality-viewer (accessed on 16 September 2024).
29. Giuffrida, A. 'Impossible to Live like This': Italy's Po Valley Blighted by Air Pollution Among Worst in Europe. *Guardian*. 2023. Available online: https://www.theguardian.com/world/2023/sep/21/italy-po-valley-blighted-air-pollution-worst-europe (accessed on 30 October 2023).
30. Comune di Bologna Open Data Comune Di Bologna. *Open Data Comune di Bologna*. 2023. Available online: https://opendata.comune.bologna.it/explore/?sort=modified (accessed on 30 October 2023).
31. Comune di Bologna Popolazione Residente per Età, Sesso, Cittadinanza, Quartiere, Zona, Area Statistica—Serie Storica. *Open Data Comune di Bologna*. 2023. Available online: https://opendata.comune.bologna.it/explore/dataset/popolazione-residente-per-eta-sesso-cittadinanza-quartiere-zona-area-statistica-/ (accessed on 30 October 2023).
32. Comune di Bologna Mappa Della Fragilità. Available online: https://www.comune.bologna.it/pianoinnovazioneurbana/mappa-della-fragilita/ (accessed on 30 December 2024).
33. Comune di Bologna Indici Di Fragilità. Available online: https://opendata.comune.bologna.it/explore/dataset/indici-di-fragilita-dal-2021/information/?disjunctive.area_statistica (accessed on 30 October 2023).
34. Comune di Bologna Parcheggi a Servizio Di Persone Disabili (H). Available online: https://opendata.comune.bologna.it/explore/dataset/sosta-veicoli-a-servizio-di-persone-disabili-h/information/ (accessed on 30 October 2023).
35. Comune di Bologna TPER—Fermate Autobus. *Open Data Comune di Bologna*. 2023. Available online: https://opendata.comune.bologna.it/explore/dataset/tper-fermate-autobus/table/?disjunctive.quartiere&disjunctive.codice&disjunctive.codice_linea (accessed on 30 October 2023).
36. Comune di Bologna Unità Gestionali. *Open Data Comune di Bologna*. 2023. Available online: https://opendata.comune.bologna.it/explore/dataset/un_gest/information/?disjunctive.classe_unita_gestionale&disjunctive.area_statistica&disjunctive.zona_prossimita&disjunctive.quartiere (accessed on 30 October 2023).
37. Istituto Geografico Militare DataBase Di Sintesi Nazionale. Available online: https://www.igmi.org/it/dbsn-database-di-sintesi-nazionale (accessed on 30 December 2024).
38. Ministero della Salute Dieci Consigli Utili. Available online: https://www.salute.gov.it/portale/caldo/dettaglioContenutiCaldo.jsp?lingua=italiano&id=5234&area=emergenzaCaldo&menu=vuoto (accessed on 20 August 2024).
39. Capelli, E.; Di Raimondo, R. Bologna e Il Suo Pilastro, Piccola Storia Utile Sul Riscatto Della Periferia—La Repubblica. Available online: https://bologna.repubblica.it/cronaca/2021/07/06/news/bologna_pilastro_compleanno_quartiere_9_luglio-306462017/ (accessed on 15 April 2024).
40. Il Resto del Carlino Il Pilastro Secondo Merola: "Non Chiamatelo Bronx". Available online: https://www.ilrestodelcarlino.it/bologna/cronaca/quartiere-pilastro-merola-ed76a21b (accessed on 15 April 2024).

41. Bologna Online IL PIANO INA CASA: NUOVI QUARTIERI POPOLARI NELLA PERIFERIA. Available online: https://www.bibliotecasalaborsa.it/bolognaonline/cronologia-di-bologna/1949/il_piano_ina_casa_nuovi_quartieri_popolari_nella_periferia (accessed on 15 April 2024).
42. Boeri, A.; Antonini, E.; Longo, D.; Roversi, R. The Redevelopment of The Heritage of Social Housing in Italy: Survey and Assessment Instruments. The Case Study of Pilastro Neighborhood in Bologna. *Procedia Eng.* **2011**, *21*, 997–1005. [CrossRef]
43. Planet Calculate an NDVI in Python 2023. Available online: https://developers.planet.com/docs/planetschool/calculate-an-ndvi-in-python/ (accessed on 30 October 2023).
44. Pinto, L.V.; Santos Ferreira, C.S.; Inácio, M.; Pereira, P. Urban Green Spaces Accessibility in Two European Cities: Vilnius (Lithuania) and Coimbra (Portugal). *Geogr. Sustain.* **2022**, *3*, 74–84. [CrossRef]
45. Niemeier, D.A. Accessibility: An Evaluation Using Consumer Welfare. *Transportation* **1997**, *24*, 377–396. [CrossRef]
46. Adamu, Z.; Hardy, O.; Natapov, A. The Impact of Greenspace, Walking, and Cycling on the Health of Urban Residents during the COVID-19 Pandemic: A Study of London. *Int. J. Environ. Res. Public. Health* **2023**, *20*, 6360. [CrossRef] [PubMed]
47. Lyu, J.; Xiang, J.; Zhao, J. Design of Bus Station Based on Sustainable Development and Humanization Designprinciples-Take Two Design Plans for Example. *MATEC Web Conf.* **2019**, *278*, 05002. [CrossRef]
48. Lyu, F.; Zhang, L. Using Multi-Source Big Data to Understand the Factors Affecting Urban Park Use in Wuhan. *Urban For. Urban Green.* **2019**, *43*, 126367. [CrossRef]
49. Zong, W.; Qin, L.; Jiao, S.; Chen, H.; Zhang, R. An Innovative Approach for Equitable Urban Green Space Allocation through Population Demand and Accessibility Modeling. *Ecol. Indic.* **2024**, *160*, 111861. [CrossRef]
50. Griggs, D.; Stafford-Smith, M.; Gaffney, O.; Rockström, J.; Öhman, M.C.; Shyamsundar, P.; Steffen, W.; Glaser, G.; Kanie, N.; Noble, I. Sustainable Development Goals for People and Planet. *Nature* **2013**, *495*, 305–307. [CrossRef]
51. Kabisch, N.; Frantzeskaki, N.; Pauleit, S.; Naumann, S.; Davis, M.; Artmann, M.; Haase, D.; Knapp, S.; Korn, H.; Stadler, J.; et al. Nature-Based Solutions to Climate Change Mitigation and Adaptation in Urban Areas: Perspectives on Indicators, Knowledge Gaps, Barriers, and Opportunities for Action. *Ecol. Soc. J. Integr. Sci. Resil. Sustain.* **2016**, *21*, 39. [CrossRef]
52. Comune di Bologna La Fragilità Demografica, Sociale Ed. Economica Nelle Aree Statistiche Del Comune Di Bologna—Edizione 2022. *Comune di Bologna*. 2022. Available online: https://inumeridibolognametropolitana.it/studi-e-ricerche/la-fragilita-demografica-sociale-ed-economica-nelle-diverse-aree-del-comune-di (accessed on 30 October 2023).
53. Mitchell, B.C.; Chakraborty, J. Landscapes of Thermal Inequity: Disproportionate Exposure to Urban Heat in the Three Largest US Cities. *Environ. Res. Lett. ERL* **2015**, *10*, 115005. [CrossRef]
54. Voelkel, J.; Hellman, D.; Sakuma, R.; Shandas, V. Assessing Vulnerability to Urban Heat: A Study of Disproportionate Heat Exposure and Access to Refuge by Socio-Demographic Status in Portland, Oregon. *Int. J. Environ. Res. Public Health* **2018**, *15*, 640. [CrossRef]
55. Mitchell, B.C.; Chakraborty, J. Thermal Inequity—The Relationship between Urban Structure and Social Disparities in an Era of Climate Change. In *Routledge Handbook of Climate Justice*; Routledge: London, UK, 2018; pp. 330–346.
56. Bergamaschi, M.; Lomonaco, A. Precarietà Abitativa e Processi Di Filtering: La Casa in Affitto per La Popolazione Straniera a Bologna. In *Esplorare il Territorio. Linee di Ricerca Socio-Spaziali*; FrancoAngeli: Milan, Italy, 2022.