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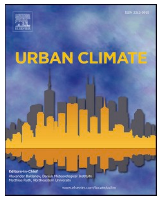

Micro-scale UHI risk assessment on the heat-health nexus within cities by looking at socio-economic factors and built environment characteristics: The Turin case study (Italy)

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ABSTRACT

Today the most substantial threats facing cities relate to the impacts of climate change. Extreme temperature such as heat waves and the occurrence of Urban Heat Island (UHI) phenomena, present the main challenges for urban planning and design. Climate deterioration exacerbates the already existing weaknesses in social systems, which have been created by changes such as population increases and urban sprawl. Despite numerous attempts by researchers to assess the risks associated with the heat-health nexus in urban areas, no common metrics have yet been defined yet. The objective of this study, therefore, is to provide an empirical example of a flexible and replicable methodology to estimate the micro-scale UHI risks within an urban context which takes into account all the relevant elements regarding the heat-health nexus. For this purpose, the city of Turin has been used as a case study. The methodological approach adopted is based on risk assessment guidelines suggested and approved by the most recent scientific literature. The risk framework presented here used a quantitative estimate per each census tract within the city based on the interaction of three main factors: hazard, exposure, and vulnerability. Corresponding georeferenced maps for each indicator have been provided to increase the local knowledge on the spatial distribution of vulnerability drivers. The proposed methodology and the related findings represent an initial stage of the urban risk investigation within the case study. This will include participatory processes with local policymakers and health-stakeholders with a view to guiding the local planning agenda of climate change adaptation and resilience strategies in the City of Turin.

Abbreviations: UHI, Urban Heat Island; H, Hazard; E, Exposure; V, Vulnerability; S, Sensitivity; AC, Adaptive Capacity; R, Risk.

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1. Introduction

The substantial number of socio-economic activities, the concentration of infrastructures, and the technological and cultural know-how which characterizes cities, have made these areas the most attractive locations for people to live (Guardaro et al., 2022; Kazmierczak et al., 2020). This process has resulted in a situation in which cities present the most significant challenges in relation to the impacts of climate change (IPCC, 2022; Barber, 2017). At the same time, cities generate high levels of energy consumption, waste production, and pollution which make them a crucial player in driving climate change from now until the end of the XXI century (Ellena et al., 2022). As the Intergovernmental Panel on Climate Change (IPCC) stated in its latest report on *Impacts, Adaptation, and Vulnerabilities*, human society is the cause of climate change (IPCC, 2022). This climate deterioration (as previously stated) exacerbates already existing weaknesses in social systems, which have likely been created by population growth and urban sprawl (Lawrence et al., 2021). In a recent report on resilient urban environments, the World Health Organization (WHO) highlighted heat events as one of the main challenges for urban planning and policy design (WHO, 2022a, 2022b). De facto, heat waves and urbanization intensify the Urban Heat Island effect (UHI) - defined as a temperature difference between urban and rural areas, caused by the excess of heat emitted and by the solar gain trapped by the urbanized environment (Araos et al., 2016; Oke, 1982). In this context, fluctuations in neighborhood microclimates reflect past design and planning choices – for example the extent of impervious surfaces (and vegetation), the mobility/transport strategy, the housing stock condition, the presence of 'waste heat' produced by air conditioning units, vehicular traffic, and industrial processes (WHO, 2022a, 2022b). Understanding how to make architecture and infrastructure in cities more resilient to heat is now at the core of a broad spectrum of research. At the root of any urban planning strategies, it must be taken into consideration that not all citizens in a given urban area may be equally affected by the same heat stress condition. In recent years, the most vulnerable populations have been identified in urban case studies using a combination of indicators concerning exposure, sensitivity and adaptive capacity and their influence on the nexus between heat stress events and health outcomes (i.e., the heat-health nexus) (Guardaro et al., 2022; IPCC, 2022; Ellena et al., 2020a). Findings over Spain, Czech Republic and Italy highlighted how the effect of heat on mortality largely varied by women compared to men and to older people compared to the youngest (Ellena et al., 2020b; Achebak et al., 2018; Urban et al., 2017 respectively). When dealing with social status variables, intra-urban variability of temperatures due to social (e.g., social isolation) (Ellena et al., 2020b; Méndez-Lázaro et al., 2018), cultural (e.g., ethnicity) (Sharma et al., 2018; Rosenthal et al., 2014), and economic (e.g., lower income/education) (Marí-Dell'Olmo et al., 2019; Sharma et al., 2018) inequalities have been highlighted as important factors, together with the characteristics of the indoor and outdoor environment that contribute to worsening heat stress conditions in indoor and outdoor environment respectively (Arifwidodo and Chandrasiri, 2020; Ellena et al., 2020a; Uejio et al., 2011).

In Italy, even though Italian citizens are among the populations most affected by heat when considering European regions (Gasparrini et al., 2015), limited analyses have been conducted to determine who, how, and where are the most vulnerable when extreme temperature conditions occur (Sanchez and de'Donato F. K V., 2021; Ellena et al., 2020a, 2020b; Breil et al., 2018). According to estimates from the WHO, Italy experienced the highest heat-related effects on daily mortality during summer temperatures (WHO, 2018). Over recent decades, northern regions within the peninsula have been characterized by a higher excess of heat-related mortality than southern regions (WHO, 2018; Michelozzi et al., 2006). To limit these negative consequences, which are largely dependent on the specific characteristics of a city, studies and analyses need to identify population vulnerabilities, as well as the risks associated with the urban setting. The most relevant demographic and socio-economic aspects should be considered in relation to health impacts from extreme temperatures. These could refer to the basic clinical fragility conditions - especially among the elderly population – as well as to social vulnerability circumstances - such as the level of education, the social isolation, or other aspects of the 'indoor' and 'outdoor' built environment (IPCC, 2022; Ellena et al., 2020a). All these elements could contribute to aggravate the vulnerability of the individual to extreme heat and cold. Hence, ad hoc climate risk assessment evaluations at the local scale, followed by the identification and the implementation of adaptative measures and interventions, are crucial to prevent climate change impacts and damages and to ensure long-term sustainability and resilience (Kazmierczak et al., 2020). Unfortunately, despite several attempts by researchers to assess the risks related to the heat-health nexus in cities, a common metric has not yet been established. This is probably because, even though climate change issues are very interdisciplinary, it is still difficult to develop common metrics by considering multiple research domains (Guardaro et al., 2022; IPCC, 2022; Ellena et al., 2020a). This is why a common metric identification is now at the hearth of the adaptation agenda in international climate negotiations (i.e., COP27 in Sharm el-Sheik) (UNFCCC, 2022). Based on these assumptions, this study aims to adopt the metrics suggested by the IPCC instead of other already existing metrics (e.g., environmental epidemiology modelling) by providing a reproducible and flexible methodology to explore the micro-scale UHI risk assessment on the heat-health nexus within cities, based on the IPCC guidelines. This is made by investigating, in detail, crucial elements of the socio-economic and of the built environment contexts. In doing so, the objectives of the study are as follows:

- identify the UHI risk for per census tract, adopting the framework proposed by the IPCC (2022) on one of the most populated Italian urban areas (i.e., city of Turin);
- identify priority areas for intervention within the territory of the city of Turin and provide useful information for local policy makers concerning what future adaptative measures could be prioritized, using as a basis, the results on the sensitivity of the population and on the adaptive capacity of the various census units within the territory.

These research questions are thoroughly explored in the paper to allow a more comprehensive overview of the urban micro-scale UHI risk assessment methodology. The paper is structured as follows: *Section 2* focuses on the research core, methods, and materials. Section *2.1* is oriented towards the contextualization of the case study under consideration; *Section 2.2* highlights the (high-resolution) spatial unit of analysis; *Section 2.3* explores the analysed factors, the data sources, and each analysed indicator; and, finally, *Section 2.4* explains the step-by-step methodology, so that it could be easily reproduced in other urban contexts. *Section 3* discusses in detail the main findings, to provide some useful recommendations for urban policymakers regarding Turin. To conclude, *Section 4* combines the arguments addressed in previous chapters, for a complete overview of the paper.

2. Methods and materials

2.1. The spatial unit of analysis

In the research, the spatial unit under analysis is the census tract which is the most granular data currently available in Italy. This is the minimum geographical entity of data collection from Italian municipalities based on which population censuses are structured (ISTAT, 2022). The city of Turin is characterized by 3.843 census tracts and an average of 300 inhabitants reside in each tract.

The orthogonal grid arrangement ensures the grid settlement corresponds approximately to the afferent sections of the census tracts, except for the hilly area and the peripheral areas of the city (due to lack of spatial homogeneity).

2.2. Factors, data sources and indicators

The factors at the base of the heat-health nexus risk presented here, were adopted based on the risk framework proposed by the IPCC (IPCC, 2022; 2014). Three factors have been analysed: *(a)* the climate *Hazard (H)*, here represented as the distribution of the hazard resulting from UHIs within the city boundary; *(b)* the *Exposure (E)*, which refers to the presence of vulnerable citizens in urban areas who are likely to be adversely affected by the occurrence of UHI phenomena: the over-65 years population; and, finally, (c) the *Vulnerability (V)*, which has been divided here into *Sensitivity (S)* and *Adaptive Capacity (AC)*. This to provide a clear distinction between (i) personal and urban environmental factors which can increase the vulnerability (and thus UHI risks on health) of the sample exposed, and, in contrast, (ii) the contextual elements which help to reduce vulnerability, thereby mitigating the health risks connected to UHI occurrences. To develop a metric, and therefore to structure the framework in a quantitative approach, specific indicators have been identified for each of the 3 factors. All the elements belonging to each factor were evaluated by taking the census tract as a spatial unit of reference. Moreover, all the steps of the data management processes were performed through the (internationally acknowledged) actions included in the open-source *QGIS software*.

2.2.1. Hazard (H)

The Urban Heat Island (UHI) phenomenon, which consists of the fact that temperatures in cities are generally higher than in surrounding rural or suburban areas, represents in certain seasons a hazard through which the health of urban populations can be compromised (Martinez et al., 2022; Heaviside et al., 2017; Oke, 1982). That is why for the hazard identification the UHI map was adopted. For this step of analysis, we used the map developed for the Resilience Plan of the city (ARPA Piemonte, 2020). The rationale behind this existing elaboration was based on two approaches: (i) the propagation of maximum temperature recorded from the in loco meteorological stations - in and around the city - during extreme temperature events, from 1753 to the present day, and (ii) the thermal

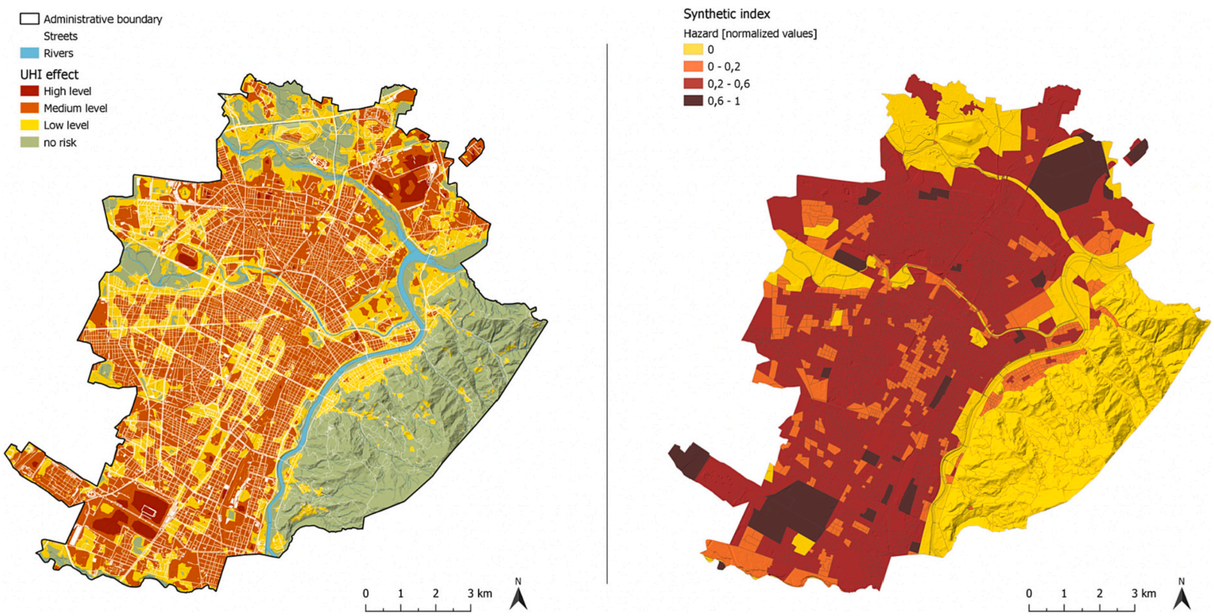

Fig. 1. From the UHI raster (left) to the UHI hazard categorization (right).

Table 1
Categories, indicators, and sources for each indicator considered within the micro-scale risk assessment framework.

Risk assessment factors		Categories	Indicators	Description	Sources	Supporting reference	ID-CODE (See Fig. 3)
CLIMATE HAZARD		–	Urban Heat Island distribution	Distribution of the UHI phenomena. 4 categorizations of hazard for each census tract.	ARPA Piemonte	Martinez et al. (2021); Heaviside et al. (2017); Oke (1982)	CH. UHI.01
EXPOSURE		–	The over-65 population	Percentage of residents aged 65 and over on the total population, per census tract.	Turin Longitudinal Study (TLS)	Martinez et al. (2021); Ellena et al. (2020b); Breil et al. (2018); Macintyre et al. (2018); Morabito et al. (2015); Leone et al. (2013); D'Ippoliti et al. (2010)	E.P.01
VULNERABILITY	SENSITIVITY	Demographic	Women over the age of 65	Percentage of resident women aged 65 and over out of the total number of people aged 65 and over, per census tract.		Ellena et al. (2020b); Veronese et al. (2019); Watts et al. (2019); Yu et al. (2010)	V.S.D.01
			Population over 85 years old (Grand old people)	Percentage of residents over 85 years of age out of the total number of people aged 65 and over, per census tract.		Martinez et al. (2021); Goldsmith (2019); Costa et al. (2017)	V.S.D.02
		Socioeconomic	Low education rate	Percentage of people with low education (primary school leaving certificate or less) out of the total number of people aged 65 and over, per census tract.		Ellena et al. (2020b); Marí-Dell'Olmo et al. (2019); Chen et al. (2018); Seebaß (2017); Koppe et al. (2004)	V.S. SE.01
			Social Isolation	Percentage of residents living in social isolation out of the total number of people aged 65 and over, per census tract.		Ellena et al. (2020b); Breil et al. (2018); Seebaß (2017); Aubrecht and Özceylan (2013)	V.S. SE.02
			Housing overcrowding	Percentage of people in overcrowded housing out of the total number of people aged 65 and over, per census tract.		Savić et al. (2018); Méndez-Lázaro et al. (2018); Gronlund et al. (2015)	V.S. SE.03
			Ethnic minorities coming from poor countries with high migration pressure	Percentage of ethnic minorities aged 65 and over out of the total number of people aged 65.		Rosenthal et al. (2014); Green et al. (2010); Kalkstein and Davis (2010)	V.S. SE.04
		Health	Presence of ischemic heart disease 410–414	Percentage of subjects with at least one hospital discharge in the period 2010–2019 with diagnosis code (principal and secondary) 410–414 out of the total number of people aged 65 and over, per census tract.		Balzi et al. (2008)	V.S.H.01
			Presence of cerebral vasculopathies	Percentage of subjects with at least one hospital discharge in the period 2015–2019 with diagnosis code 430–438, excluding 435 out of the total number of people aged 65 and over, per census tract.		Tancioni et al. (2008)	V.S.H.02
			Presence of Heart Failure	Percentage of subjects with at least one hospital discharge in 2012–2019 with principal diagnosis code 402, 428, 4254, 4255, 4259, 78,550, 78,551, 39,891, 40,401, 40,403, 40,411, 40,413, 40,491, 40,493, out of the total number of people aged 65 and over, per census tract.		Saczynski et al. (2012)	V.S.H.03

(*continued on next page*)

Table 1 (*continued*)

Risk assessment factors		Categories	Indicators	Description	Sources	Supporting reference	ID-CODE (See Fig. 3)
			Presence of diabetes	Percentage of subjects with hospital discharge in the period 2015–2019 with diagnosis code 250 or with at least 2 prescriptions (red prescriptions and F-file) of anti-diabetes drugs (ATC code A10) on different dates in 2019 or presence in the Regional Diabetes Register (January 2020 update) as at 31/12/2019, out of the total number of people aged 65 and over, per census tract.		Di Domenicantonio et al. (2018); Gnavi et al. (2008)	V.S.H.04
			Presence of BPCO	Percentage of subjects with no exemption for 'asthma' and at least 4 drug prescriptions in different months in 2019 of: inhaled adrenergic, systemic adrenergic, anticholinergic xanthine derivatives or with at least one exemption with code 024 active in 2019 or with at least one hospital discharge with principal diagnosis of COPD or one discharge with principal diagnosis for related causes to COPD and with COPD in secondary diagnoses in 2017–2019, out of the total number of people aged 65 and over, per census tract.		Anecchino et al. (2007)	V.S.H.05
		Environmental Context	Residential buildings in poor conditions	Percentage of buildings in poor condition on the total of the building, per census tract.		Mutani et al. (2020); Maller and Strengers (2011)	V.S. EC.01
			Building density	Ratio of built volume, per census tract.	Geographical Database of Piedmont Region (BDTRE)	Kim et al. (2014)	V.S. EC.02
			Population density	Ratio of total residents, per census tract.	BDTRE; ISTAT	Henseke and Jürgen (2014); Hondula and Barnett (2014)	V.S. EC.03
			Distance from watercourses	Identification of census tract within a 100 m radius of the main watercourses (rivers: Po, Sangone, Stura di Lanzo, and Dora Riparia).	BDTRE; ISTAT	Hsu et al. (2016)	V.S. EC.04
	ADAPTIVE CAPACITY	Indoor and outdoor environmental attributes	Percentage of green area	Ratio between green areas spaces on the total area per census tract.	BDTRE; ISTAT	WHO (2016); Henseke and Jürgen (2014)	V.AC. IOEA.01
			Average number of floors	Average number of floors in buildings per census tract.	BDTRE; ISTAT	Walikewitz et al. (2018)	V.AC. IOEA.02
			Possibility of conversion to green roofs	Average number of horizontal roofs per census tract.	BDTRE; ISTAT	Sharma et al. (2018)	V.AC. IOEA.03
		Neighbouring facilities	Proximity to social welfare facilities	Identification of census tract within 100 m from hospitals, social welfare facilities, advice centers and pharmacies.	BDTRE; ISTAT	Inostroza et al. (2016)	V.AC. NF.01
			Proximity to cool places	Identification of census tract within 200 m from shopping centers, libraries, and cinemas.	BDTRE; ISTAT	Bradford et al. (2015)	V.AC. NF.02

dispersion coming from the (infrared thermal bands) analyses by satellite images (i.e., Landsat and ASTER satellites) under recent heat wave occurrences (Ponte, 2017). Therefore, for this initial phase of analysis, each pixel of the existing UHI raster (see left panel of Fig. 1) was first aggregated into single polygons based on similarities of values who composed them. In a second step, this information has been transposed into a shapefile to attribute a specific UHI value to each census tract. At this stage, using the natural breaks algorithm (i.e., Jenks) within *QGIS*, the hazard has been categorised into 4 classes: high (0.6–1), medium (0.2–0.6), low (0.01–0.2), and null (0) (see right panel of Fig. 1). Such a statistical method, often used in GIS, is structured on approximate approaches to simplify the restitution of data on a map for non-misleading grouping classes.

2.2.2. Exposure (E)

When considering the exposure of the urban population under extreme percentile of temperatures (i.e., 1st, 5th, 95th and 99th), most recent literature on European regions agrees on the fact that the oldest corresponds to the population most impacted when considering the health outcomes (i.e., mortality and morbidity) (Martinez et al., 2021; Breil et al., 2018; Macintyre et al., 2018; Morabito et al., 2015; Leone et al., 2013; D'Ippoliti et al., 2010). A recent study which analysed heat- relative risks (RR) and attributable fraction of mortality (AF) among different social and demographic groups in Turin showed this aspect was particularly pronounced within Turin (Ellena et al., 2020b, 2022). For this purpose, for the exposed sample this research took into account the percentage of residents aged 65 years and over per census tract (data updated by 2022). This information came from the Turin Longitudinal Study (TLS), a study built to monitor metropolitan health variations and understand how socioeconomic factors related to health issues. Each record, built through deterministic individual record-linkage procedures, includes the demographic (i.e., age and gender) and the socioeconomic information (i.e., education, social isolation, marital and professional status) collected by the population censuses and health information (i.e., hospital discharge records, mortality, and pharmaceutical prescriptions) from several statistical and administrative sources (Costa et al., 2017). Moreover, the current residence address within TLS permitted to assign for each individual a specific census track (of residence). Data for these area-based indicators come from the Regional Environmental Protection Agency (ARPA Piemonte), the Leading Innovation and Knowledge for Society (LINKS Foundation) and from other information systems of the Metropolitan City of Turin. Also in this case, the natural breaks algorithm (i.e., Jenks) was applied through *QGIS,* with the aim to categorise the exposure in grouping classes. More details about the exposure indicator are presented in Table 1.

2.2.3. Vulnerability (V)

For the identification of vulnerability-related elements, two distinct groups of indicators were considered. As previously mentioned, the first related to *Sensitivity (S)* and the second concerned *Adaptive Capacity (AC)* (IPCC, 2022; 2014). All the indicators selected for the identification of the two groups resulted from a comprehensive review of literature about the useful elements to consider within the heat-health nexus at the urban scale (WHO, 2022a, 2022b; Martinez et al., 2021; Ellena et al., 2020a; Breil et al., 2018). It is important to mention how, for these groups related to the vulnerability, it was very challenging to match datasets attributable to the census tracts. Therefore, the listed indicators have been considered so far:

- In terms of *Sensitivity*, the elements which contribute to the susceptibility of the exposed sample have been considered here. Based on urban adaptation guidelines published by the World Health Organization (WHO, 2022a, 2022b), by the European Environmental Agency (EEA) (Breil et al., 2018), and by updated scientific papers in the field (Ellena et al., 2020a), four different categories of determinants have been structured.

1. D*emographic*, which included elements related the gender (i.e., women) (Ellena et al., 2022; Veronese et al., 2019; Watts et al., 2019; Yu et al., 2010) and the oldest (i.e., the grand old people: over 85 years old) (Martinez et al., 2021; Goldsmith, 2019; Costa et al., 2017);
2. *Socioeconomic*, composed by social and economic drivers such as education (Ellena et al., 2022; Marí-Dell'Olmo et al., 2019; Chen et al., 2018; Seebaß, 2017; Koppe et al., 2004), social isolation (Ellena et al., 2022; Breil et al., 2018; Seebaß, 2017; Aubrecht and Özceylan, 2013), housing overcrowding (Savić et al., 2018; Méndez-Lázaro et al., 2018; Gronlund et al., 2015), and ethnic minorities coming from poor countries with high migration pressure (Rosenthal et al., 2014; Green et al., 2010; Kalkstein and Davis, 2010);
3. *Health*, which (in)directly refer to principal chronic diseases considered by the Regional Chronicity Plan (PRC), such as ischemic heart disease (Balzi et al., 2008), cerebral vascular disease (Tancioni et al., 2008), heart failure (Saczynski et al., 2012), diabetes (Di Domenicantonio et al., 2018; Gnavi et al., 2008), and COPD (Anecchino et al., 2007);
4. E*nvironmental context* includes indicators related to the contextual characteristics of the environment which cannot be subject to short- and medium- changes as a result of planning variations aimed at reducing climate change risks. The indicators here included are the following: the percentage of residential buildings in a poor state of preservation (Mutani et al., 2020; Maller and Strengers, 2011), the building density (Kim et al., 2014), the population density (Henseke and Jürgen, 2014; Hondula and Barnett, 2014) and, finally, the areas characterized by remoteness from watercourses (Hsu et al., 2016).

Categories belonging to *Sensitivity*, the corresponding indicators, their description as well as the sources from which they originate and from which their consideration in the analyses is based are presented in Table 1.

- In terms of *Adaptive Capacity (AC),* all those physical elements and practical services of the urban environment which contribute to more favourable conditions for the individual under extreme temperatures events were here included. Also in this case, following existing categorization (Ellena et al., 2020a), the indicators were divided in two categories:

1. *Indoor and outdoor environmental attributes*, which refers to the physical elements of the urban built environment that contribute to alleviating heat stress conditions, such as the percentage of green areas (WHO, 2022a, 2022b; Ellena et al., 2020a; WHO, 2016; Henseke and Jürgen, 2014), the average number of floors (Walikewitz et al., 2018), and the possibility of flat roof conversion into green roof (Sharma et al., 2018).
2. *Neighbouring facilities*, which include indicators related to the proximity to places within the city that can help reduce heat stress through the services they offer, such as social welfare facilities (Inostroza et al., 2016) and proximity to cool places (Bradford et al., 2015).

As for the previous sub-factor, indicators belonging to *Adaptive Capacity*, their description, together with the sources from which they derived and the sources that justified their consideration in the analyses are provided in Table 1.

Overall, all categorizations by indicators (e.g., low education rate), sub-factors (e.g., sensitivity), and factor (i.e., vulnerability) were based on the natural breaks algorithm available in *QGIS software*.

2.3. Micro-scale risk assessment in the heat-health nexus context: The methodology

The methodological framework adopted in this study is based on a microscale risk assessment according to the methods suggested and approved by the most recent literature (IPCC, 2022; Pede et al., 2022; De Vivo et al., 2022; GIZ and EURAC, 2017; RAMSES, 2017). Therefore, the risk analysis here involved a quantitative outcome per census tract, based on the interaction of three main factors: *(a) Hazard (H)*, *(b) Exposure (E)*, and *(c) Vulnerability (V)*. In fact, efficient adaptation actions to prevent and/or reduce climate risks should be defined on targeted analysis based on climate trends, as well as the reference system and its characteristics (IPCC, 2022; WHO, 2022a, 2022b). Specifically, the IPCC's latest Assessment Report on '*Impacts, Adaptation, and Vulnerability*' emphasized how in doing so it is crucial to consider the most vulnerable populations, as there is a vicious cycle in climate hazards perpetuating existing social inequalities (IPCC, 2022; Islam and Winkel, 2017). Inequalities lead to greater exposure and vulnerability of disadvantaged groups to climate risks and as a result, disadvantaged groups suffer disproportionate losses of income and assets. In parallel, due to a lack of resources and capacity building, those affected by stronger inequalities are not well prepared to meet emission reduction targets (mitigation) and/or address climate-related risks (adaptation) (UNFCCC, 2022; Islam and Winkel, 2017). Therefore, with reference to the above-mentioned citations, the first step was to collect data for each indicator related to the 3 factors of the microscale risk assessment (step 1, Fig. 1). All data were collected by census tract, which corresponded to a total of 3.852 units. After collecting and analysing the data, the min-max normalization has been applied by using the following formula (De Vivo et al., 2022; GIZ and EURAC, 2017; GIZ, 2017):

$$X_i = x_i - x_{min}/x_{max} - x_{min} \tag{1}$$

where x_i represented the individual data to be transformed, x_{max} corresponded to the highest value, and x_{min} to the lowest value for each indicator. In this way, each X_i parameter was identified by a numerical value from 0 to 1, where the highest value corresponded to the highest contribution to each factor, considered separately from the others. This procedure allowed all indicators of each of the 3.852 census tracts to be transformed into a range from 0 to 1, facilitating cross-comparability and their evaluation (step 2, Fig. 1). At this stage, the development of *H* and *E* factors have been done, by using a linear aggregation method where we assigned equal weight (*w*) to each indicator (i.e., $w = 1$) (step 3, Fig. 1) (De Vivo et al., 2022; GIZ and EURAC, 2017; GIZ, 2017). Such an approach for this phase of analysis was chosen to avoid further subjectivity in the development of the first stage micro-scale risk assessment (Xiang et al., 2022), but experts judgment will be included in further studies to evaluate how the risks coming from the preliminary analyses might vary from those including local expert judgements. In the case of *V*, the approach was slightly more complicated. This was because this factor is composed of two groups of sub-factors: *Sensitivity (S)* and *Adaptive Capacity (AC)*. Regarding *S*, in line with what was done for *H* and *E*, the min-max normalization formula was applied after data collection, followed by the linear aggregation approach. In contrast, for the computation of *AC*, the change of the sign was applied before its aggregation (GIZ, 2017) (step 4, Fig. 1), due to the nature of its information. This is because the higher the *AC* value, the lower the *V*. Once *S* and *AC* was estimated, we proceeded with the estimate of the total *V* per census tract (step 5, Fig. 1). In this case, the aggregated *V* index implies a simple average of the *S* (with 15 indicators) and of the *AC* indices (with 5 indicators). Overall, we assumed that all the indicators were of equal importance and, thus, we weighted them equally. Finally, to obtain a Global Risk Index for each of the 3.852 census tracts (step 6, Fig. 1), the following formula was applied:

$$\text{Risk} = \text{H x E x V} \tag{2}$$

The resulting product between the 3 different factors led to a single risk value (i.e., net risk) by census tract, which has been normalised (i.e., normalization of risk values obtained) and categorised (i.e., categorization of risk values) into 4 classes based on the *quantile method* provided by the open-source *QGIS software* (step 7, Fig. 1). To give a clear overview of the applied step-by-step methodology, Fig. 2 highlights the main activities for evaluating the UHI micro-scale risk assessment.

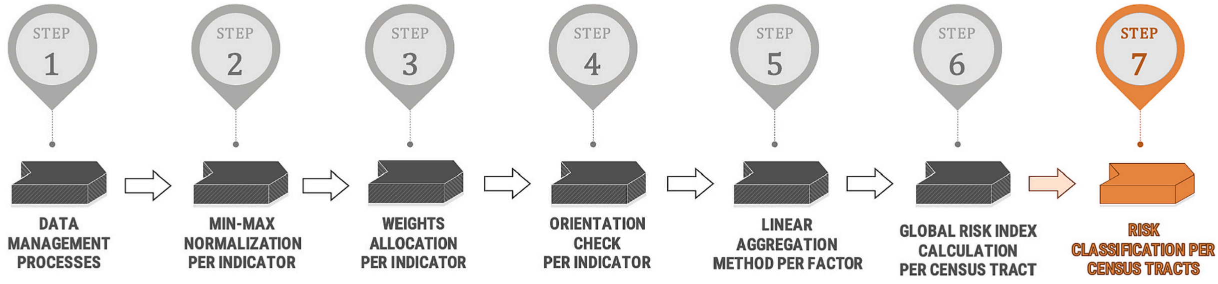

Fig. 2. Micro-scale urban risk assessment framework: the step-by-step process.

2.4. *Case study: The city of Turin (northwest of Italy)*

With around 845.409 inhabitants, Turin is the largest city in northwest Italy, and it is the fourth most populated Italian urban area. Due to the presence of the Alpine Mountain chain on one side and the Superga hills on the other, Turin is characterized by a limited circulation of the foehn winds, which gives the city a complex mosaic of microclimates, with dry summers and mild wet winters (specific features of the Mediterranean climate) (Ellena et al., 2022; Ellena et al., 2020b). In the 50s and 60s, the city was affected by a social and economic transition that generated different waves of migration from other territories within the country (especially from the southern regions) and has left a legacy of 10 million square metres of abandoned industrial spaces (ARPA Piemonte, 2020). According to a recent study from Ponte (2017), these urban spots are characterized by mean temperatures of about 3 °C higher than the city's average during extreme events, with a spatial buffer of 50 m in the surroundings. Overall, the territory of Turin is densely urbanized, with 8.418,35 ha of soil consumed, which corresponds to 64,69% of the city's total surface area (SNPA, 2020). To cope with the impacts of climate change, which have become increasingly evident over the last decades (Spano et al., 2021; Ellena et al., 2020b; Legambiente, 2020; ARPA Piemonte, 2020), in 2015 the City participated within the Life DisastEr Risk Reduction InSurance Life DERRIS Project (DERRIS), which developed a context-specific assessment over the industrial contexts, and which led to a general Resilience Plan for the city (Spano et al., 2021; ARPA Piemonte, 2020; Ponte, 2017). In addition, this study is one of the products of the CCM Climactions project (Ministero della Salute, 2022), in which Turin has been used as a pilot case.

3. Results

This chapter presents the results of the methodology described in *section 2.3*. For each factor included in the micro-scale UHI risk assessment, a corresponding map has been produced, to provide an understanding of the spatial differentiation of the values by census tract, and thus have specific information about the current UHI *Hazard (a)* diversification, the population *Exposure (b)*, the associated *Vulnerabilities (c)*, and on the final risk. In this respect, Fig. 3 presents a comprehensive mapping per *(a)*, *(b)*, *(c)* factor.

The *Hazard* map *(a)* in Fig. 3 highlights the distribution of the current UHI phenomena categorised into 4 classes, from "high" (in red) to "null" (in green). The *H* resulted in null over the hilly area (south-east) of the city corresponding with the main urban parks which demonstrates the significant contribution of vegetation to heat reduction. In contrast, the historic centre and the surrounding residential areas presented a variegated *H* (from low to medium), while some areas in northern and southern census tracts were marked by higher values (in red). In fact, as suggested by previous studies over Turin (Ponte, 2017), the highest score of UHI in Turin corresponds to large industrial areas; those characterized by a high percentage of impervious surfaces and absence of greenery. This spatial distribution of the UHI hazard may be at a countertrend to what would be expected when considering UHI phenomena in most European cities, however, this relates with the results of the UHI analyses conducted in loco (ARPA, 2020; Ponte, 2017). This finding should be viewed with the understanding that a mapping of past/current UHI does not necessarily presume the same location (or magnitude of the hazard) in the future, according to the Shared Socioeconomic Pathways (SSPs) under consideration. Notwithstanding, the extensive literature assumes the relevance of current UHI mapping differentiation as a decision-support instrument.

With respect to the *Exposure* (b), which is based on the ratio of the population of the total inhabitants who are over 65 years out of total, the distribution was not uniform; therefore, it was not easily interpretable. However, it emerged that a significant number of census tracts located in the northern part of the city corresponded to lower levels of exposure. These areas are characterized by high migration rates, which often corresponds to younger population subgroups. Similar assumptions (i.e., about younger population) can be made in respect to areas located in the surroundings of industrial complexes which is probably due to the proximity to workplaces.

The *Vulnerability (c)* distribution within each census tract of the city is - as expected - in line with the one observed within studies about socioeconomic inequalities in Turin (Costa et al., 2017): higher values in the northern census tracts, starting from the Dora River. However, to provide a clearer representation of the indicators that compose *Sensitivity* (c.1) and *Adaptive Capacity* (c.2), Fig. 4 illustrates the distribution of each indicator (identified by the ID Code in Table 1) (for a clear description of the inclusion of these components within the overall UHI risk framework, see section 2.3). At this stage of analysis, through the applied step-by-step methodology, a detailed risk identification by census tract was produced, allowing a clear understanding of the areas most at risk from the occurrence of UHI phenomena. Therefore, Fig. 5 presents the spatial distribution of the UHI risk on a sub-urban scale (*R.01*), the categorization of the risks through the already mentioned normalization processes (*R.02*), and the areas to prioritize in case of future planning intervention (*R.03*) at the urban and sub-urban scale.

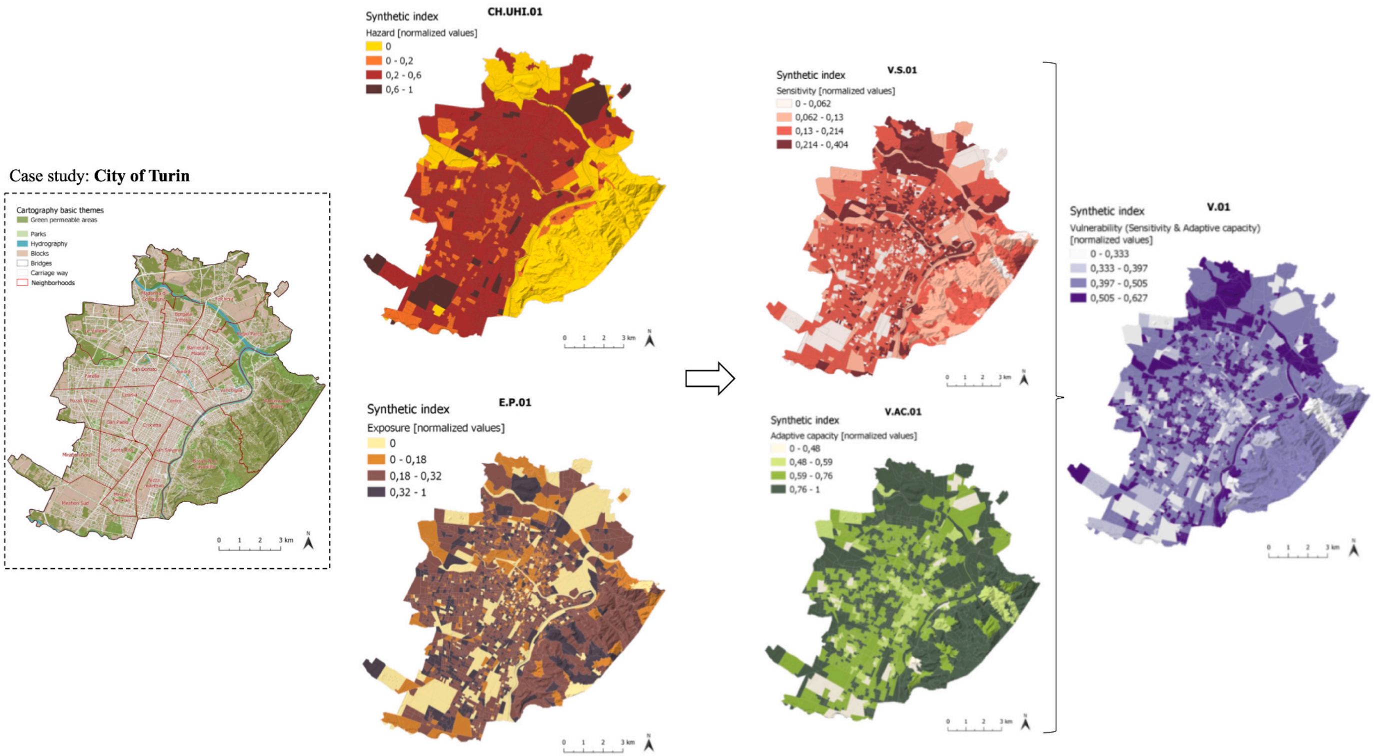

Fig. 3. Mapping the factors underpinning the UHI risk assessment: *Hazard (a)*, *Exposure (b)*, and *Vulnerability (c)*.

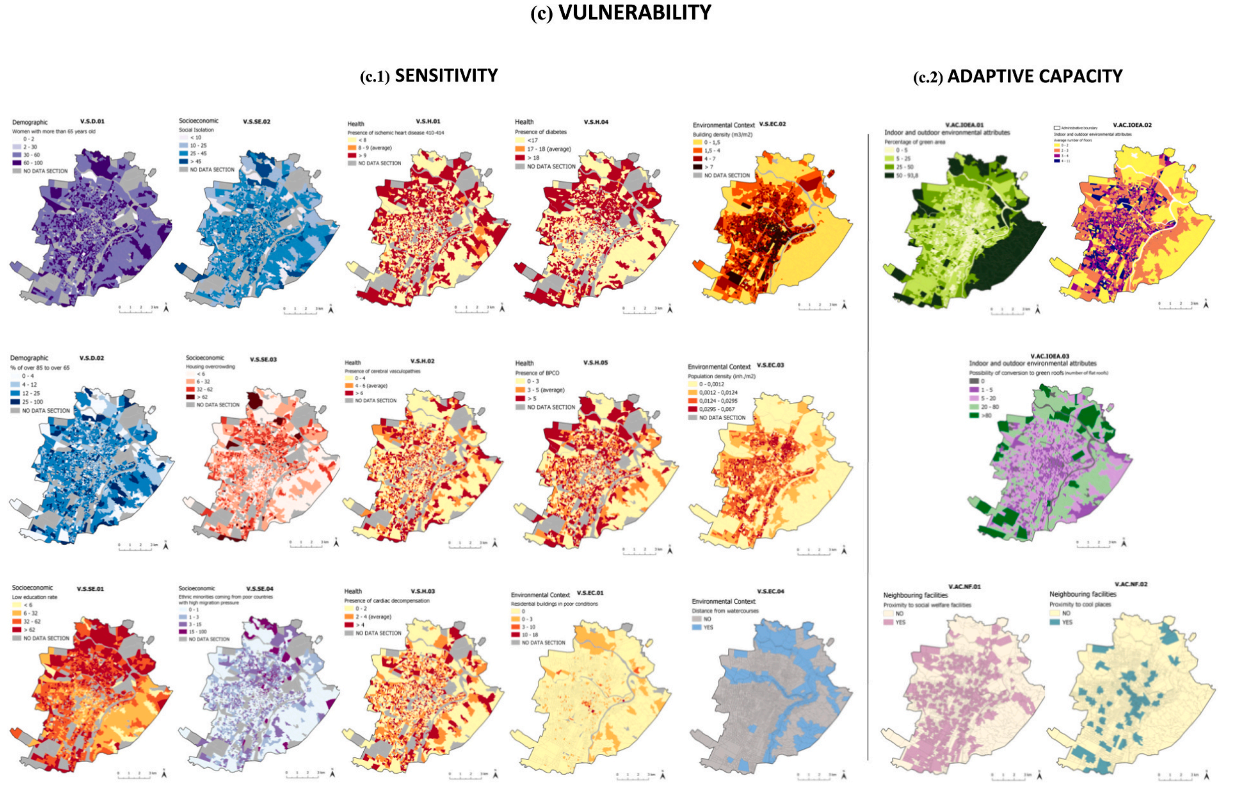

Fig. 4. Mapping the factors underpinning the *Sensitivity (c.1)* and the *Adaptive Capacity (c.2)* factors within the UHI risk assessment framework.

The proposed results enable the identification of the UHI risk within the city boundaries of Turin as well as the priority areas for intervention, based on the past/current UHI phenomena spatial distribution and most recent characteristics of citizens at the census tract scale. Overall, higher-risk zones are mostly located in the densely populated areas of the suburbs (i.e., Barriera di Milano in the north, Mirafiori north, and Mirafiori south, Parella, and Pozzo Strada, and Vanchiglietta), while the city center is under medium risk. In addition, the large industrial areas - which most recent literature regarding Turin frequently links with high UHI hazard scores – do not appear here at high risk, since they are mostly un-inhabited. This emerging spatial pattern of risk distributions may also be contrasting to what might be expected when considering the UHI risk in European context. Nevertheless, it is necessary to emphasize that by combining the spatial distribution of the heat island effect with the location of the most fragile population (strongly concentrated in the suburbs) and considering the identified low adaptive capacity of those areas (associated with the settlement and urban quality of the

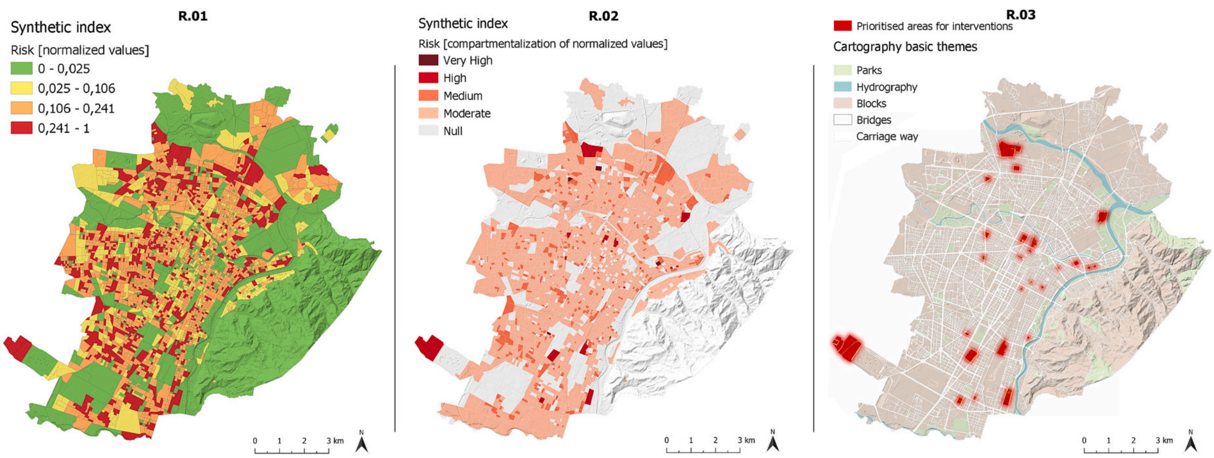

Fig. 5. Mapping the UHI risks (R.01; R.02) and the prioritized areas for intervention (R.03).

suburbs), such an outcome appears more than justified. To conclude, as briefly mentioned before, these findings could be viewed as one of the tools to support the guiding assumption for short- and medium- term strategic planning processes. And, to ascertain, with less uncertainty, the achieved distribution of UHI risks, these maps must be compared to high-resolution mortality and morbidity mapping - whenever available. When looking at future UHI risk distribution, climate data on future scenarios (e.g., RCPs or SSPs) need to be incorporated within the proposed methodology to determine more precisely what the expected future impacts of climate change on heat islands might be for the city of Turin.

4. Discussion

Our analyses correlate with most recent research observations relating to the heat-health nexus in the urban context. Ranking of the final risks highlighted higher scores in areas characterized by a consistent quantity of impervious surfaces. In the most densely populated areas these are often characterized by higher scores of economic and social disadvantages (IPCC, 2022; Ellena et al., 2022; Ellena et al., 2020a). More specifically, a stronger UHI resulted more relevant in relation to several industrial and residential areas located in the north (−west) and in the south (−east) of the city, as well as within the historical centre, which in this case is characterized by narrow streets and six-storey buildings with high density. When Vulnerability was considered the findings have been driven by the available data on social and economic factors of citizens as well as on the high-resolution outdoor built environment components (Sanchez and de'Donato F. K V., 2021; Ellena et al., 2020a). In this context, during the 20th century, Turin's population was significantly affected by industrialization, which, with its associated flows of immigration from other parts of Italy, contributed to changes in living conditions, the social and demographic organization, as well as the structure of the city's urban environment (Ellena et al., 2020b; Costa et al., 2017). In the 1960s, many of the city's high-density residential areas were built around industrial sites in a very short period, with few public spaces and services and characterized by impermeable surfaces, dark buildings materials, a lack of tree-lined avenues and green areas, in which the most emission- and heat-generative production activities are still located (Prat and Mangili, 2016). Albeit some differences in socio-economic conditions, these neighbourhoods are still in the original conditions when looking at residential morphology and building structures. This could partially explain and justify the outdoor preconditions of each census tract. In other words, past planning policies and decisions still influence the UHI risks in cities. All the analysed indicators were believed to be of crucial importance by the authors, since to understand the geography of health within an urban context, it is necessary to examine the distribution of social disadvantages and of the urban built environment (WHO, 2022a, 2022b; Ellena et al., 2020a; Costa et al., 2017). In conclusion, higher-risk zones and areas considered high priority for intervention are mostly located within densely populated sections of the suburbs (i.e., Barriera di Milano in the north, Mirafiori north, and Mirafiori south, Parella, and Pozzo Strada, and Vanchiglietta), while medium-risk zones correspond to the city centre. In addition, industrial areas - often identified as high-risk to UHI by most recent literature - do not appear to achieve a high/significant score of risk, because they are scarcely inhabited in this case. These findings contrast in some ways with the Heat-related Elderly Risk Index (HERI) analyses from Morabito et al. (2015) regarding the city of Turin in which the city centre corresponded to a "very high" score (Morabito et al., 2015). This may be because this research study analysed the distribution of the UHI phenomena (hazard) combined with the age of the population (people aged 65 or over) (exposure) - but did not consider other socio-economic and built environment indicators (vulnerability) that the literature indicates as crucial within risk assessment analyses in the context of extreme temperatures. In general, these findings support a view to develop strategic adaptation measures against UHI risk to the population of Turin. This is an innovative aspect since such an extensive urban-scale investigations over Turin have not been yet implemented (Ellena et al., 2022; Ellena et al., 2020b). To further validate the results, a comparison with environmental epidemiology studies outcomes by census tract (i.e., relative risks (RR) and/or attributable fraction of mortality (AF)) would be appropriate. This would require a joint assessment by two different methods (one more interdisciplinary and one strictly epidemiological), thus facilitating an in-depth validation of the results and, thereby, reducing any uncertainty in the current findings.

Concerning the methodology, the metric here proposed has been already presented and described in previous studies (De Vivo et al., 2022; Ellena et al., 2021; GIZ and EURAC, 2017; GIZ, 2017), but such an in-depth application for determining the distribution of UHI risks within an urban context among citizens - based on the IPCC theoretical framework - is still uncommon. This may be both because of data availability (useful in the optic of empirical studies), but also due to difficulties encountered in the practical application of such an interdisciplinary approach (UNFCCC, 2022). In fact, to date, such a methodology that considers both climate hazard, epidemiological data together with socio-economic inputs at the international level is still needed, but under identification/development (UNFCCC, 2022; WHO, 2022a, 2022b). The reason for this may be related to the gap of available empirical studies - such as the one proposed - within the health-related sector under climate change circumstances.

4.1. *Strength, limitations, and future development*

There are two key strengths of this research. The first is that such a high-resolution analysis to explore the connection between the UHI hazard, the population exposure, and the related vulnerabilities at the urban level - to use as an example to reproduce similar analyses in other urban contexts - is still uncommon. Census tracts represent the smallest territorial entity for which population data are available in many countries (e.g., US, Canada, EU), and – as such – the proposed methodology could be used to reproduce similar analyses in other urban areas by considering at once all the elements underlying the risk. The substantial number of info (i.e., datasets) allowed a more detailed estimation of how the risk from UHI is diversified within the city of Turin and filled relative knowledge gaps around climate change issues. Secondly, the applied methodology for determining the distribution of UHI risks within an urban context is based on the proposed up-to-date IPCC theoretical framework. As such – this application can be used as a standard to support - in term of capacity building processes - those urban areas which are in the process of developing a high resolution UHI risk assessment on the past/current situation by looking at the health of the inhabitants. Since the applied methodology is flexible and easily manageable, more up to date (and/or new) hazard, exposure and vulnerabilities indicators at the census tract-level could be added at any time based on the context under analysis. As a more comprehensive perspective, a definition of indicators and methodologies to use as a common base to monitor the links between health and climate change is at the heart of the international climate discussions, such as at the negotiation tables of the Conferences of the Parties (UNFCCC, 2022) and within the Lancet Countdown dialogues (and reports) (Di Napoli et al., 2022). Of no less importance, it is the recognition that these analyses might be used to undertake further evaluations with a view to determining future risk trends from UHI under different emissive scenarios (e.g., RCPs or SSPs). This will allow policymakers to better understand the adaptation measures which need to be prioritized to mitigate the expected risks in the short-, medium-, and long- term. However, it is also necessary to recognise some significant limitations at this stage of analysis. Due to the time constraints of the project, the indicators have each been combined with the same value (i.e., weight), based on the assumptions that they had an independently established effect on the final risk and this effect is of equal value. Therefore, in any future investigations, the indicator weighting processes must take into account (i) the causal chain of mechanisms through which these indicators would influence the risk; (ii) the fact that some of the selected indicators treat variables that have a solid demonstration of being determinants of risk (e.g. presence of heart failure), while some others are only potentially predictors (e.g. ethnic minorities); and (iv) the distinction between indicators geographically correlated with each other, while some others are independent. Nonetheless, the process of risk assessment is iterative and structured over multiple and diversified steps (IPCC, 2022; WHO, 2022a, 2022b; GIZ, 2017). Therefore, this research, as well as other up-to-date studies with the same type of analysis (De Vivo et al., 2022; Ellena et al., 2021; GIZ and EURAC, 2017; RAMSES, 2017; Dong et al., 2014; Aubrecht and Özceylan, 2013) usually start with an assessment without weights, which then could be incorporated with additional insights. Another limitation of the study relates to the inclusion of air quality data within the analyses. The area under the jurisdiction of the Turin department is one of the most critical in Europe in terms of air pollution, particularly in the plain area (Robotto et al., 2022; Khomenko et al., 2021). For this reason, it would be very valuable to include $PM_{2.5-10}$, O_3 and/or NO_x data (among others). Nonetheless, to date air quality monitoring stations from ARPA follows a non-homogeneously pattern across the city of Turin, aspect which would imply an arbitrary attribution to the census tracts in case of use. For this reason, the study did not integrate these data into the evaluation processes. Finally, this study did not include engagement with local stakeholders (such as health policy makers, urban planners) despite being highly recommended as iterative processes (IPCC, 2022; GIZ and EURAC, 2017; RAMSES, 2017). Their inclusion within the analyses could contribute to add relevant information “from the ground” (i.e., bottom-up approach) from local collaboration and partnership. Their involvement can also increase local awareness and help to identify climate related risks in urban areas. This issue is under consideration for future research, through the adoption of ad hoc questionnaires and through the involvement of key local policy makers and stakeholders.

5. Conclusions

This study - conducted as part of the CCM Climactions project (Ministero della Salute, 2022) – and using Turin as a subject, has improved the knowledge base for the implementation of micro-scale UHI risk assessment by looking at the heat-health nexus within cities. To the best of our knowledge, is the first time that such an in-depth methodology is applied in an Italian city. This methodology considered both epidemiological data together with climate and socio-economic indicators at the microscale, and - as such - could be considered as a standard metric to evaluate the UHI risk assessment at the sub-urban scale. To date, a better understanding of the indicators and metrics to apply to evaluate the impacts of climate change over the population is among the top priorities to be identified by the international community (UNFCCC, 2022; WHO, 2022a, 2022b). This approach could support developing policies towards a more climate-resilient future and, therefore, reduce the expected losses and damages under extreme heat conditions (Di Napoli et al., 2022).

CRediT authorship contribution statement

Marta Ellena: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Giulia Melis:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Nicolás Zengarini:** Data curation, Conceptualization, Visualization, Writing – review & editing. **Eduardo Di Gangi:** Data curation, Formal analysis, Investigation, Visualization, Writing – review & editing. **Guglielmo Ricciardi:** Formal analysis, Investigation, Methodology, Writing – review & editing. **Paola Mercogliano:** Visualization, Writing – review & editing, Funding acquisition. **Giuseppe Costa:** Visualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

The data that has been used is confidential.

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