AESTIMUM 2020 Special Issue: 57-80

Climate change and urban well-being: a methodology based on Sen theory and imprecise probabilities

Iacopo Bernetti[1],
Elena Barbierato[1,*],
Irene Capecchi[1],
Claudio Saragosa[2]

[1] *Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Italy*
[2] *Department of Architecture (DIDA), University of Florence, Italy*

E-mail: iacopo.bernetti@unifi.it; elena.barbierato@unifi.it; irene.capecchi@unifi.it; claudio.saragosa@unifi.it

The phenomenon of urban heat waves are becoming a significant public health problem in the summer season. Global warming is therefore not only an environmental problem, but also an ethical and political issue of climate justice. The research was based on the capability approach developed by Amartya Sen. The aim of the study is to (1) identify a set of indicators that allows to estimate the risk of decreased individual well-being; (2) implement these indicators in a probabilistic model that allows to explicitly consider the lack of certain knowledge on the effects of climate change; (3) provide high resolution urban mapping for climate change adaptation strategies.
The research focused on the vulnerable people (elderly people and children) in the city of Rosignano Solvay.
The combination of the results, obtained through the aggregation Dempster's rule, allows to identify the most critical areas on which it is necessary to intervene or through mitigation or urban regeneration.

Keywords: *Urban heat island, Cities and climate change, Capability approach, Imprecise probabilities, Dempster Shaffer Theory, Urban planning.*
Parole chiave: *Isola di calore urbana, Città e cambiamenti climatici, Approccio di capacità, Probabilità imprecise, Teoria di Dempster-Shaffer, Pianificazione urbana*
JEL codes: *Q54*, *I30*, *I14*

*Corresponding author

1. Introduction

Climate change certainly has several consequences for human health, both direct and indirect. High temperatures can cause respiratory and cardiovascular problems among children and elderly, also leading the elderly to premature deaths (Zhang, McManus and Duncan, 2018). Different types of extreme weather events affect different regions: for example, heat waves are a problem especially in southern Europe and the Mediterranean, but also, to a lesser extent, in other regions. This phenomenon affects the thickness of the atmosphere and causes warm air subsidence, abnormal air heating and a stable urban heat island (UHI) in the region (Ghobadi et al., 2018). Therefore, the phenomenon affects cities livability and influences the ways in which its outdoor spaces are used. Especially, public spaces intended for use by pedestrians and cyclists, such as parks, squares, residential and commercial streets, and foot and cycle paths are used and enjoyed more frequently when they have a comfortable and healthy climate.

DOI: 10.13128/aestim-8086

The Intergovernmental Panel on Climate Change (IPCC) reports that heat waves increased toward the end of the 20th century and are projected to continue to increase in frequency, intensity, and duration worldwide (Meyer et al., 2014), leading to future increases in illnesses and mortality. The extended exposure to extreme heat can severely affect a person's physiological comfort, causing heat stress (Aminipouri et al., 2016; Mortensen et al., 2018; Reid et al., 2009), resulting in influence on the ways in which the people use the outdoor spaces, in particular public spaces intended for use by pedestrians and cyclists (e.g such as parks, squares, residential and commercial streets, and foot and cycle paths). Therefore, the research is increasingly focused on the analysis of the spatial distribution of temperatures in urban areas, on the analysis of measurements of mitigation and adaptation to climate change, on adverse health impacts from heat waves and on the identification of the most vulnerable population groups to heat, to identify some useful guidelines to prevent harm. According to Isoard and Winograd (2013), the adaptation strategies in Northern Europe they are based on the ecosystem by small-holder farmers (Sweden); in mountain areas on insurance policies against natural hazards (Switzerland); in Central and Eastern Europe on the restoration of the lower Danube wetlands to manage flood risks; in Northwest Europe on flood risk management in the Scheldt estuary (Belgium), on adaptation strategies based on the ecosystem and green infrastructure (Netherlands), on the restoration of peatlands (Ireland), on the management of flood risk and the Thames Barrier (United Kingdom) and on floods, fresh water and the Dutch Delta Programme (Netherlands). Finally, in the Mediterranean Region they are based on technological, monitoring and survey actions as part of Integrated coastal management (France), on desalination for water supply (Spain), on new varieties and production systems in the wine sector (Spain), on regional early warning systems supporting people's health and safety (Italy). Indeed, it is important to consider that global warming is not only an environmental problem, but also an ethical and political issue of climate justice. This is because the effects of global warming not only affect the ecosystem - the life of plants and animals - but also that of human beings. For these reasons in 2000, at the same time as the United Nation Climate Change Sixth Conference of the Parties (COP 6), the issue of Climate Justice was defined. Climate Justice therefore means the moral obligation to create a more just and equitable world starting from the protection of human rights, and in particular of those populations that suffer most from the effects of climate change, even though they are not directly responsible for them (Opinion of the European Economic and Social Committee on "Climate Justice", 2017).

Theories of climate justice have produced important methodological approaches at a global level, for example the polluter pays principle (UNCED, 1992) and the models of distribution of emissions, but these models have limits because they are mainly focused on prevention/mitigation structures, leaving the crucial dimension that regards how we can really adapt to the growing effects of climate change strongly underestimated (Hughes, 2013).

To bridge the gap between the ideal and abstract notions of the theory of justice and the reality of defining social policies, the capability-based approach developed by Amartya Sen and Marta Nussbaum (1993) was introduced. This approach takes into account the local/individual sphere as it is based on what individuals are capable of doing. (Robeyns, 2016). Sen has directly addressed the issue of the environmental basis of existing capacities by recognizing that «*variations in environmental conditions, such as climatic circumstances (temperature ranges, rainfall, flooding, and so on), can influence what a person gets out of a given level of income.*» (Sen, 2014, p. 70). Therefore, environmental circumstances can have a significant impact on individuals' ability to use resources and build social relationships. By extending the list of capabilities proposed by Nussbaum in a framework to deal with climate change, Edward Page (2007) proposes the addition of an ability to live in a safe and hospitable environment. Holland (2008), on the other hand, underlines the way in which the capabilities on the Nussbaum list depend directly on a stable climate system. Schlosberg (2012) stresses the importance of mapping vulnerability can help us understand the expected environmental impacts and threats to basic human capabilities that are based on the continuous functioning of environmental processes and conditions. This vulnerability mapping can be used to design policies that address these vulnerabilities. A committed reflection process that assesses vulnerability can be used to clarify which policy responses are most needed in particular areas and where resources will be applied more appropriately on separate issues. Similarly Lindley et al. (2011) define the concept of socio-spatial vulnerability. «*Socio-spatial vulnerability brings in aspects of place and time with personal, social and environmental factors resulting in the geographical expression of the degree to which an external event has the potential to convert into well-being losses*». (Lindley et al., 2011, p.6). (Heat waves)

Heat waves do not depend on the absorption of solar energy by asphalted and concrete surfaces as for the urban heat island (UHI), but are extreme weather conditions that occur during the summer season, characterized by high temperatures at the above the usual values, which can also last for a long period. It is considered an extreme climate which can be a natural disaster and a danger because heat and sunlight can overheat the human body (Kyselý, 2002; Meehl and Tebaldi, 2004; Theoharatos, 2010).

The aim of the study is to (1) identify a set of indicators that allows to estimate the risk of decreased individual well-being following significant changes in access to the basic capabilities of Sen and Nussbaum; (2) implement these indicators in a probabilistic model that allows to explicitly consider the inaccuracy and the lack of certain knowledge on the effects of climate change; (3) provide a methodological approach to define a high resolution urban mapping suitable to drive climate change adaptation strategies aimed to reduce heat related risks for the vulnerable population and prevent their health risks. The research focused on the social groups most vulnerable to heat waves: elderly people over 65 and children, in a case study represented by Rosignano Solvay town, a little-size city located on central Italy.

2. Methodologies

2.1 The capability approach to urban climate risk

Amartya Sen's capability approach focuses on the substantial freedom of people to pursue their vision of individual well-being. According to the theory outlined by Amartya Sen, the well-being of the individual is defined by the human "functionings" and the "capabilities" to achieve it. Functions are what a person is able to do or be given his income, but also his personal characteristics (e.g. his state of health) and the characteristics of the environment in which he lives. A person's capabilities, by contrast, reflect «*the alternative combination of functionings [they] can achieve, and from which he or she can choose one collection*» (Nussbaum and Sen, 1993,p. 31). «*Capability*», Sen writes elsewhere, «*is a kind of freedom: the substantive freedom to achieve alternative functioning combinations*» (Sen, 1999, p.75). Sen argues that each person should enjoy roughly similar sets of capabilities to achieve a comparable level of well-being.

Sen's approach to capabilities was further developed by Martha Nussbaum. A central pillar of Nussbaum's theory of justice is the definition of a classification of capacities. While Sen provides numerous examples of capabilities and functions, he has so far refused to offer a systematic list of capabilities or to define their relative importance. Nussbaum, on the contrary, identifies a list of 10 "central human functional capacities": life; bodily health; bodily integrity; senses, imagination and thought; emotions; practical reason; affiliation; relationship with other species; play; political and material control over one's environment (Nussbaum, 2006a, 2006b).

A strength of capability theory is that it potentially leads to a detailed description of the impact of climate-related events on individual well-being. With regard to heat waves, high temperatures affect all individuals in a given area, however the conversion of the extreme event into a loss of well-being will depend on how personal, social and geographic characteristics affect individuals. Let us first consider the fundamental ability of Nussbaum "Bodily health". With regard to personal characteristics, the elderly and children will be more vulnerable. Taking into account the social characteristics, poor, lonely or foreign people will have less chance of implementing family adaptation strategies (Robeyns, 2005).

However, the geographical characteristics of the urban environment can also influence the variation in well-being from the heat wave. The distance that you need to travel outdoors during an extreme climatic event to go to church, shops or other places of social life can represent a discomfort so serious as to limit the freedom of individual behaviour. This affects important capabilities such as "Senses, Imagination, and Thought", "Emotions", "Affiliation", etc.

In our research, we therefore classified the indicators into two vulnerability sub-set referring exclusively to the vulnerable population (elderly and children): vulnerability deriving from people's socio-economic conditions and vulnerability deriving from the risk of exposure to heat waves in outdoor activities. The first sub-set derives from the socio-economic characteristics of the elderly and children

Table 1. Social vulnerability and exposure vulnerability indicators.

Population	Indicator	Data source
Elderly	*Social Vulnerability*	
	Density population 65-69 years old Density population 70-74 years old Density population over 74 years old Density of low education Density of widower Density of population for rent	Census data (ISTAT, 2011)
	Exposure vulnerability	
	Churches distance Bus stop distance Medical studies distance Pharmacies distance Food services distances Supermarkets distances	GIS data analysis (Open Street Map)
	Urban climate safety	
	Urban climate safety	Comfort index (Barbierato et al. 2019)
Children	*Social Vulnerability*	
	Density population less 5 years old Density population 5-9 years old Density of low education Foreigners	Census data (ISTAT, 2011)
	Exposure vulnerability	
	Schools distance Urban parks distance Sport areas distance	GIS data analysis (Open Street Map)
	Urban climate safety	
	Urban climate safety	Comfort index (Barbierato et al. 2019)

population, while the second from the risk of exposure deriving from the distance between the commercial, social and transport services and the places of residence of the sensitive population(Inostroza et al., 2016).

According to the literature (Eisenman et al., 2016; Fraser et al., 2017; James et al., 2015; Krellenberg, et al., 2015; Loughnan, et al., 2014; Mendez-Lazaro et al., 2018; Morabito et al., 2015; Reid et al., 2009; Uejio et al., 2011; Zhang et al., 2018) we have identified the set of urban vulnerability indicators of sensitive people shown in Table 1. For the first set of indicators the demographic and socio-economic variables investigated included age, poverty, education level and living alone. For the second set of indices we calculated the pedestrian distances from churches, bus stop, pharmacies and medical offices. The highest vulnerability of the elderly to heat is related to age, because they dehydrate themselves more easily due to age-related reduced thirst and the capacity to conserve salt and water (European Topic Center on Climate Change Impacts, Vulnerability and Adaptation, 2012). In the paper we considered three class of elderly population (65-69 years old, 70-74 years old, over 74), starting from the assumption that the greater the age the greater the vulnerability to heat. In according to Krellenberg, et al. (2015), Mendez-Lazaro et al. (2018), Reid et al. (2009), the higher the educational level, the lower the vulnerability as higher educational level contributes to better knowledge about natural extreme events and the ability to anticipate and resist. For these reasons we chose illiterate, population with primary school and with secondary school to identify as low level of instruction to identify the vulnerable people.

Other factor concerned the household composition, because people living alone are more vulnerable to heat (Eisenman et al., 2016; Reid et al., 2009; Uejio et al., 2011; Zhang et al., 2018). Renters often have little autonomy and surplus for mitigation measures, may lack capacities to cope with consequences of a hazardous incident (Cutter et al., 2008; Jean-Baptiste et al., 2011). In additional to these factors, we considered also the pedestrian distance from a principal services that a heat sensitive person is used daily to attending (Eisenman et al., 2016; Fraser et al., 2017; James et al., 2015; Krellenberg et al., 2015).

Following Page (2007a, 2007b) the list of capabilities proposed by Nussbaum can be extended to address the problems of future climate change by expanding the list to include a new capability «*to represent the value a person derives from operating within a hospitable natural environment.…Here, we view a safe and hospitable environment as a vital ingredient of a decent life rather than a facilitator of other functionings such as 'play', 'emotions' or'control over one's environment' (which, despite its label, has no direct connection to environmental values). ... On this view, we should value a hospitable environment because it is an integral feature of a life of decent quality and not because it facilitates desire satisfaction.*» (Page, 2007b, p.464).

In our work we therefore considered a specific indicator to evaluate the capability of people to live in an urban environment with a safe and hospitable climate in public spaces (streets, squares and urban parks). To evaluate the urban climate safety, we analyzed the current land surface temperature of the study area and the temperature perceived by people through a climatic comfort index. The geodatabase used for the construction of our index was a high resolution (1 meter) land surface temperature map (LST), calculated on a day of urban heat wave. The basic spatial data at 1 meter resolution is crucial for the entire development of the methodology, because the unit used to also create the membership classes by geolocalizing the fuzzy indicators.

The main feature of the map is to consider the effect of the presence of the urban green, the bodies of water and the shadow of the buildings on the surface temperature (for more details see Barbierato et al., 2019). The date of the heat wave to which the map refers is August 8, 2017, it falls within the 95th percentile of the frequency distribution of the maximum daily temperature in the last 14 years of survey of the weather station of Quercianella (a town 9 km away from

Rosignano). It should be noted that the date of August 8 is purely representative of an increasingly probable generic heat wave day (for a review see Ummenhofer and Meehl, 2017). On this day, the LST in the urban area of Rosignano recorded a median of 33.8 °C and a range of 28 °C for the first quartile (in the shade of the tree crowns) and 37 °C for the third quartile (in the east-west oriented roads). The LST map has been converted into a Thermal Sensation Index (TS) map based on the procedure proposed by Givoni et al. (2003):

$$TS = 1.7 + 0.1118 \cdot T_a + 0.0019 \cdot RS - 0.322 \cdot v - 0.0073 \cdot RH + 0.0054 \cdot T_{ss} \quad (1)$$

where T_a is air temperature in °C, *RS is the* horizontal solar irradiance in W/m^2, v is the wind speed in *m/s*, *RH is the* relative humidity in *%*, T_{ss} *is the* surrounding soil temperature in °C. The index is defined as the perception of cold or heat, on a scale ranging from 1 (very cold) to 7 (very hot). Level 4 is comfortable, which means the human body feels no thermal discomfort.

2.2 Imprecise probabilities and Dempester-Shafer theory

Climate change assessments and the development of response strategies are hampered by multiple uncertainties and lack of knowledges. Some sources of uncertainty can be represented by objective probability density functions. There are, however, limits to the deterministic description of the phenomenon given that the set of consequences of urban heat waves on individual well-being is certainly not a stationary system. The reliability of knowledge of uncertain aspects of the world (such as the "true" value of climate vulnerability) cannot therefore be represented by objective probabilities.

One method to characterize the uncertainty due to the lack of scientific knowledge is the Bayesian (or subjective) probabilities, which refer to the degree of credence of the experts, considering the available data. Caselton and Luo, (1992) argue that decision problems related to climate change are decision-making processes in conditions of "almost ignorance". "Almost ignorance" occurs when "*the total information brought to bear on the decision problem is sufficiently weak to present difficulties with conventional uncertainty analyzes.*"(Caselton and Luo, 1992, p. 3071) Numerous approaches have been proposed in the literature to overcome the limitations of the Bayesian scheme, considered too rigid to deal with problems in conditions of "almost ignorance" through the generic concept of "imprecise probability" (Walley, 1991). In the context of climate change vulnerability analyzes (the scheme that has been most widely applied is the theory of Dempster Shaffer (DST) (Dempster, 1967, 1968a, 1968b, 1969; Shafer, 1976, 1982).

The DST derives from the Bayesian theory of subjective probabilities and allows the combination of different lines of evidence that originate from various sources of knowledge and information in order to obtain degrees of belief for different hypotheses. In our study we have defined two lines of evidence: the first, H1: climate vulnerability, is related to the probability that a vulnerable person (elderly or child) will cross a generic urban place outdoors on a heat wave day; the second, H2: urban climate resilience, is linked to the probability that the same position has microclimatic characteristics (presence of urban greenery, high ratio between the height of the buildings and the width of the road, north-south orientation of the roads, etc.) that reduces the health risk for the elderly and children.

The treatment of uncertainty in DST focuses on the concept of "plausibility". The Bayesian formulation represents the starting point of the treatment of the notion of plausibility in DST; the two approaches share the idea that plausible reasoning is a type of uncertain reasoning because it is carried out using sources that provide information characterized by a degree of reliability but not of certainty. Unlike Bayesian probabilities, DST does not need complete information in the event space; therefore, this theory allows the use of two different values to express belief in a specific proposal, or belief in its negation.

If we have two lines of evidence H1 and H2, the concept of DS subjective probability (*p*) differs from the concept of Bayesian probability because for two lines of evidence in the DS theory we will have:

$$p(H1) + p(H2) + p(H1,H2) = 1 \text{ and thus } p(H1) + p(H2) < 1, \quad (2)$$

while in Bayes:

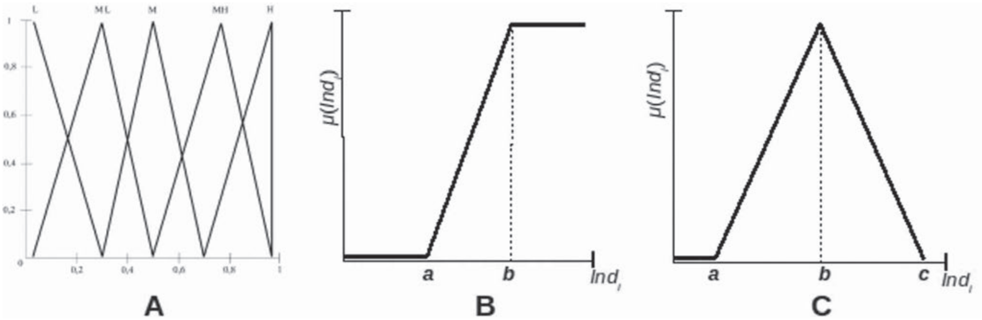
$$p(H1) + p(H2) = 1. \quad (3)$$

The remaining *p*(H1,H2) represents the contribution to uncertainty. The concept of DST lines of evidence differs from the concept of Bayesian probability because in Bayesian probability the sum of probabilities is constrained to 1 instead in DST the contribution to uncertainty is taken in account. In the DST we have high uncertainty when we have strong evidence of vulnerability and strong evidence of urban climate safety in the same location. The evaluation of the hypothesis is based on the concept of Basic Probability Assignment (BPA). The BPA represents the contribution that a certain factor *i* gives as a support for a specific line of evidence (for instance the vulnerability of a location). In our approach, the evaluation of BPA is based on the fuzzy functions (Yager, 1999) built on the indicators of table 2 and linguistic evaluators which were used in the model (expressed as a degree of belief). The evaluators were given by experts as oral terms (Bentabet et al., 2000); model formulation was explained in the following formula:

$$BPA_{i,x} = \mu_{linguistic}(Ind_i) \cdot \mu(x_i), \quad (4)$$

were $\mu_{\text{linguistic}}(Ind_i)$ is the linguistic assessment through a fuzzy linguistic evaluator of the contribute in the line of evidence of indicators *i* (Ind_i) and $\mu(x_i)$ is the assessment through a membership function of the environmental effect of the indicators i on the localization *x*. A membership function for a fuzzy set A on the universe of discourse X is defined as $\mu A{:}X \rightarrow [0,1]$, where each element of X is mapped to a value between 0 and 1. This value, called membership value

Figure 1. Linguistic fuzzy numbers: L=low, ML=medium-low, M=medium, MH=medium-high, H=high.



or degree of membership, quantifies the grade of membership of the element in X to the fuzzy set A. Membership functions allow us to graphically represent a fuzzy set. The x axis represents the universe of discourse, whereas the y axis represents the degrees of membership in the [0,1] interval (Porębski et al., 2016). We carried out the evaluation through linguistic quantifiers through a procedure that was carried out with the contribution of experts in the pediatric and geriatric medical sector. The opinions of three urban planning experts have been elicited using linguistic terms that can be expressed in trapezoidal fuzzy numbers. The evaluation of the variables was therefore implemented through a set of linguistic terms derived from Chen and Hwang's scale 3 (figure 1). The fuzzification of the indicators was based on the information deduced from the literature examined (Eisenman et al., 2016; Fraser et al. 2017; James et al., 2015; Krellenberg et al., 2015). Fuzzy functions have been applied to indicator maps through map algebra procedures. The maps are all at 1 meter of resolution. The basic probability assignment maps (BPA) were finally obtained through the product of each fuzzy map and the relative linguistic weight. The parameters of the trapezoidal fuzzy functions and the linguistic terms used are shown in table 2 (see also figure 1). For example, a low linguistic weight was attributed to the distance from schools factor to evaluate the well-being of children since in Italy, during the school period (from September to June of the following year), the season hit by the waves has a short duration.

For the line of evidence H1, urban climate vulnerability, all factors are progressively aggregated in pair using the orthogonal sum (Shafer, 1976) rule of combination:

$$BPA_x(i,j) = BPA_{i,x}\_|\_BPA_{i,y} = \frac{BPA_{i,x}\cdot(1-BPA_{j,x})}{1-BPA_{i,x}\cdot BPA_{i,x}}. \quad (5)$$

The final result mass probability of urban climate vulnerability *m(H1)* is obtained by the follow procedure:

$$m(H1) = \_|\__v^{H1}(BPA_{v,x})v = 1,\cdots,V \quad (6)$$

Table 2. Fuzzy function parameters.

Indicator	Linguistic assessment	a	b	c
Density of elderly population 65-69 years old	medium	0	15	
Density of elderly population 70-74 years old	medium-high	0	20	
Density of elderly population over 74 years old	high	0	36	
Density of low education population	low	0	97	
Density of widover	high	0	26	
Density of population for rent	medium-low	0	17	
Churches distance	high	250	1500	
Bus stop distance	medium	250	1500	
Medical studies distance	low	250	1500	
Pharmacies distance	low	250	1500	
Population density less 5 years	high	0	19	
Population density between 5-9 years	medium	0	16	
Foreign population density	low	0	18	
Distance from schools	low	250	1500	
Distance from urban parks and public gardens	medium	250	1500	
Distance from sports and recreation areas	medium	250	1500	
Urban climate safety	high	1	4	7

were _|_ is the orthogonal sum, $v=1,...,V$ are all indicators of vulnerability and $r=1,...,R$ are all indicators of urban climate safety.

For line of evidence H2, urban climatic resilience, it was calculated on the basis of the TS map using the following procedure:

$$m(H_2) = \mu_{linguistic}(TS) \cdot \mu(x_{TS}) \tag{7}$$

where $\mu_{linguistic}(TS)$ is the expert linguistic assesment of contribute of TS to the line of evidence, $\mu(x_{TS})$ is the membership function of urban cliamte resilience of TS in location x.

The aggregation of the two hypothesis *H1* and *H2* is performed adopting Dempster rule the uncertainty degree of location derive both from occurrence of high vulnerability and high urban climate safety in the same area:

$$\begin{aligned} Bel(H1) &= \frac{m_{H1} \cdot 1 - m_{H2}}{1 - m_{H1} \cdot m_{H2}} \\ Bel(H2) &= \frac{m_{H2} \cdot 1 - m_{H1}}{1 - m_{H2} \cdot m_{H1}} \\ U(H1,H2) = Bel(H2) - (1 - Bel(H2)) &= \frac{(1 - m_{H1}) \cdot (1 - m_{H2})}{1 - m_{H2} \cdot m_{H1}} \end{aligned} \tag{8}$$

Bel(H1) and Bel(H2) are belief of vulnerability and belief of urban climate safety measures; belief interval represents the uncertainty degree of location, deriving both from occurrence of high vulnerability and high urban climate safety in the same location. The adopted methodological framework is summarized in figure 2a and 2b.

3. Study area

The research was applied in the city of Rosignano Solvay a small city of Central Italy located on the Tuscan coast and overlooking the Tyrrhenian Sea. The study area has boundary coordinates (datum WGS84, projection UTM, zone 32) N min = 613253, N max = 618615, E min = 4803895, E max = 4807895, and mean latitude = 43.39°N.

Since the aim of the research is focused on the urban well-being and it is to provide an urban-scale mapping for adaptation strategies to climate change to reduce heat risks for the vulnerable population, the perimeter of the study area only takes into account the urbanized territory of Rosignano Solvay and Castiglioncello and it excludes: industrial areas to the south of the city, some neighbouring areas that are too far from the city centre and those that are on the border with rural areas have been excluded from the municipal territory (Figure 3).

The urbanized territories had a different urban and settlement development. The history of Rosignano Solvay revolved mainly around the soda plant opened in 1913 by the industrialist Ernest Solvay. An urban nucleus was immediately created around the plant, consisting of houses for employees and workers of the plant itself. With the expansion of the factory, the villages were also expanded, building some groups of houses beyond the railway line towards the coast, also enhancing services. The 1940s were decisive for urban development, since the frenetic building activity gave the industrial town its current image: the avenues, the trees, the squared lots, the vegetable gardens, the architecture and the pine forests constitute the typical "style Solvay " (Celati and Gattini, 1995).

While, the urbanized area of Castiglioncello is located in a privileged position from a panoramic point of view, far from the major communication routes, it remained unknown and uncontaminated until modern times, with its pine forests and cliffs close to the sea. Since the 1960s it has become a popular seaside resort, consisting of establishments and holiday homes and villas surrounded by greenery (Celati and Gattini, 1991).

The study area covers an area of 586 100 hectares, which 224 257 ha of urban green and the remaining part by artificial surface.

The territory of Rosignano Solvay falls in the "Hot-summer Mediterranean climate" class according to the classification of Köppen and Geiger. Regions with this form of the Mediterranean climate typically experience hot, sometimes very hot and dry summers. In this season the population, 20 340 total inhabitants in 62 census tract in according to ISTAT data on 2011 population census, is very vulnerable to heat waves, in particular the categories most at risk for heat-related health are

Figure 2a. Structure of the Dempster Shaffer model of the elderly population.

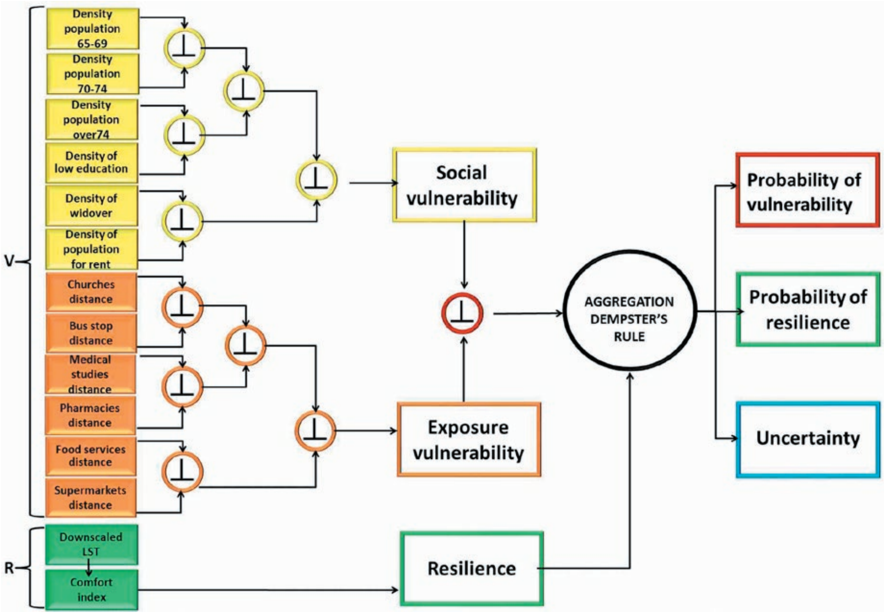


Figure 2b. Structure of the Dempster Shaffer model of the infant population.

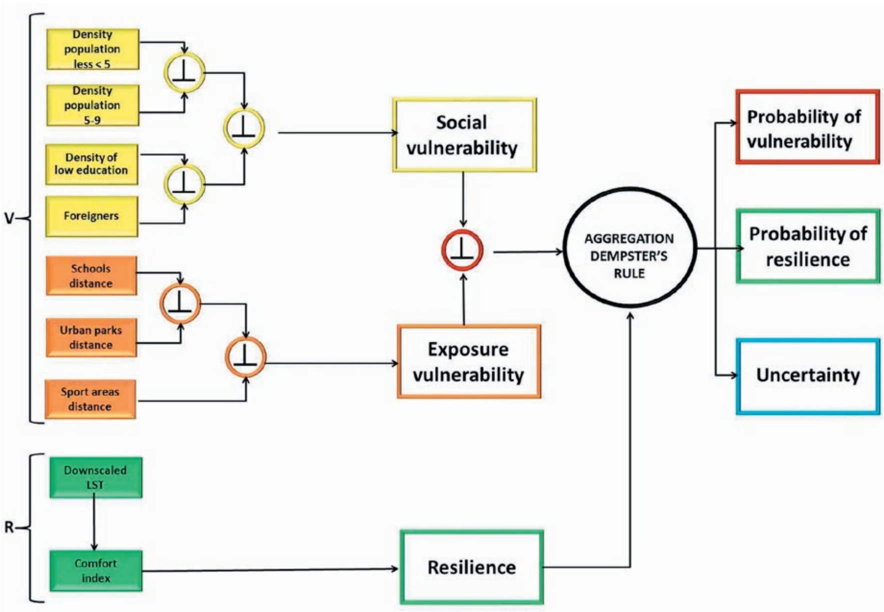
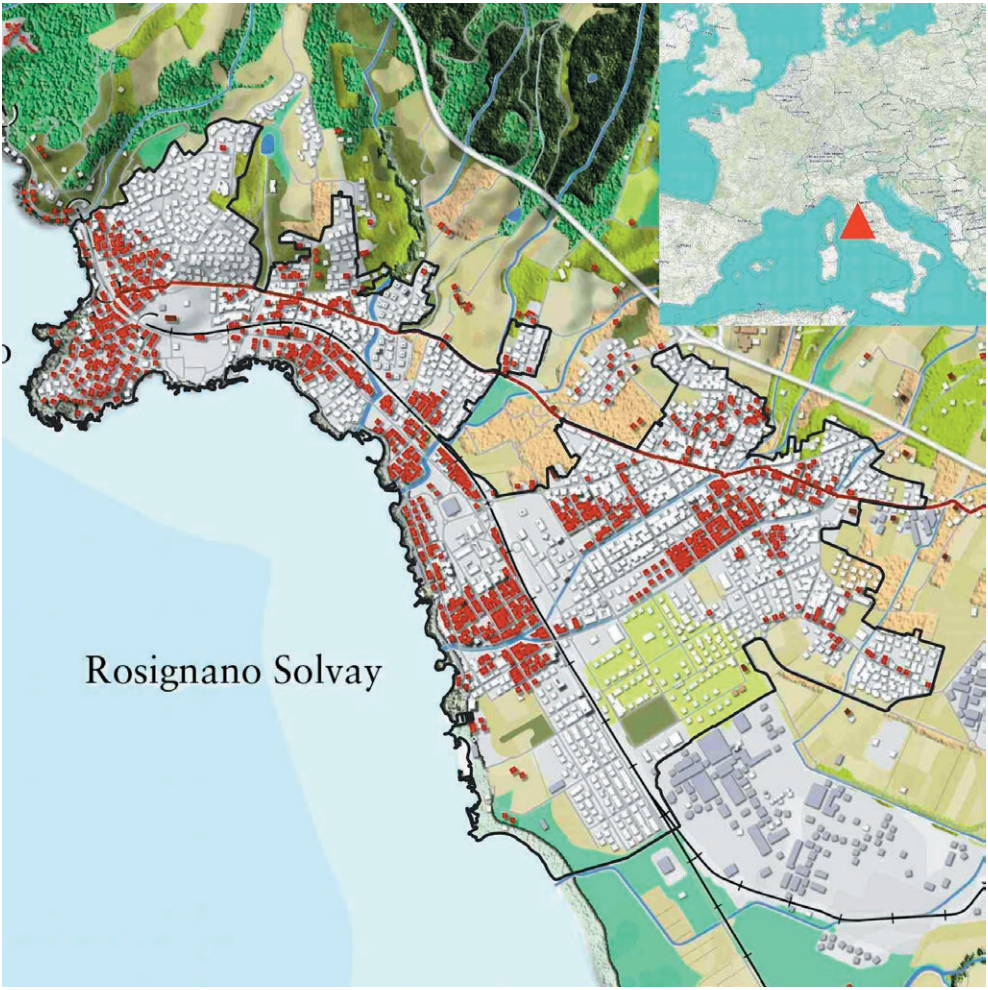


Figure 3. Study area.



the following: 7.70% children until 9 years old, 27.57% are people over 65 years old, 9.85% are widowed, 46.14% have low education, 10,82% are graduates, 5,11% are foreigners and finally 5.68% are rented families .

These two areas, although forming a continuous urbanized territory, have very different properties and building typologies also on the basis of the values of the real estate market. According to the Revenue Agency database (2019), in the south of the study area the civilian houses are between 1500 and 2100 €/mq, the economic houses between 1400 and 1900 €/mq, the villas between 2300 and 2850 €/mq. However, in the north the prices are significantly higher, because civil homes are between 1900 to 2650 €/mq, villas between 2300 and 3300 €/mq.

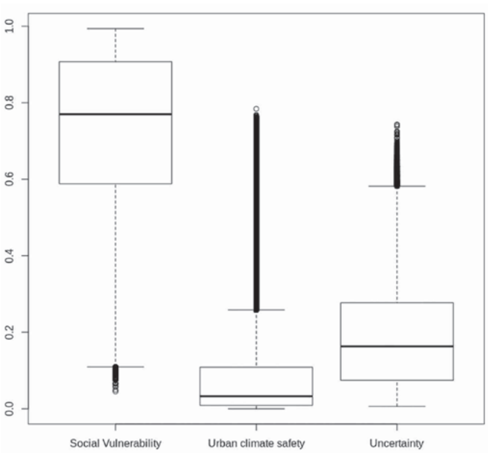
4. Results

Table 3 and Figure 4 show the parameters of the probability distributions calculated using the Demspter Shaffer model described in the previous paragraph.

The probability of having an elderly population in conditions of social vulnerability on a heat wave day reveals critical values, with an average of 0.72 and a median of 0.77. The distribution is also very asymmetrical towards high risk values, with the first quartile equal to 0.59. Even in the case of the infant population, there is a high risk of social vulnerability with a median of 0.71 and the first quartile of 0.5.

Even the chance to live in a safe urban environment for climate-being is severely impaired in a heat wave days. For the elderly we have a median of 0.08

Figure 4. Left: Boxplot of frequency distribution for Elderly. Right: Boxplot of frequency distribution for Children.



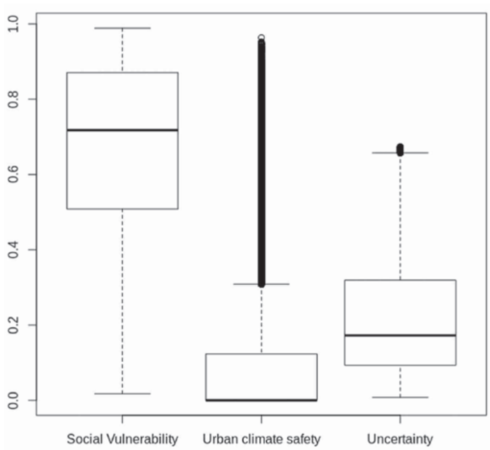


Table 3. Frequency distribution parameters of Belief of Social Vulnerability, Belief of Urban Climate Safety and Uncertainty for elderly and children.

	Elderly			Children		
	Social Vulnerability	Urban climate safety	Uncertainty	Social Vulnerability	Urban climate safety	Uncertainty
Min.	0.045	0.000	0.006	0.017	0.000	0.008
1st Quartile	0.588	0.009	0.074	0.508	0.000	0.093
Median	0.770	0.033	0.163	0.718	0.000	0.172
Mean	0.728	0.086	0.186	0.678	0.100	0.222
3rd Quartile	0.907	0.109	0.277	0.871	0.124	0.319
Max.	0.993	0.784	0.743	0.989	0.964	0.674

and a third quartile of 0.1, while for children we have 0.1 and 0.12 respectively. However, the two distributions have a relatively long right tail with maximum values of 0.78 for the elderly and 0.96 for the children; this shows that even on a day of climatic emergency there are areas in the study area that are likely to be a safe environment, because of the configuration of the space, the shape and height of the buildings and the presence of green areas and corridors.

The uncertainty of the two assessments is relatively low: for the elderly there is a median of 0.16 with the first and third quartiles equal to 0.07 and 0.28 respectively; for children there is a median of 0.17 with the first and third quartiles respectively equal to 0.09 and 0.32.

The general risk condition highlighted by the total results is geographically differentiated. Figures 5a and 5b highlights how the indicators of social vulnerability are higher in the south and south-east areas of the study area, in particular for the density of population with low degree of education, elderly people, widowers and rented families.

The climate comfort index (figure 6) also recorded safer values in the north area and in a part of the south area while the most critical values are concentrated in the south-east area.

This situation results in a strong inequality for the different areas of the city in relation to the risk of a decrease in well-being due to social vulnerability and a decrease in the capacity of living in a safe urban environment for both the elderly and children. In figures 7 and 8 the probabilities of social vulnerability, urban climate safety and uncertainty have been inserted respectively in the red, green and blue bands of an RGB image, thus generating a "false color" map defined by the triangular legend shown in the figures.

Figure 7 shows how the most critical situations for the elderly are located in the central-southern area of the city (colors from red to purple). This in fact presents a high probability of social vulnerability, a low probability of a safe climate environment and low uncertainty. The north-west area (unfortunately small in size) is more resilient to extreme thermoclimatic events (green colors), with good urban environmental safety values and low probability of social vulnerability. The areas where uncertainty prevails (colors from blue to purple) are relatively rare and scattered in the study area. The detail at the top right (figure 7b) shows that even in areas with the highest social vulnerability, the presence of public green areas considerably improves thermoclimatic well-being.

Figure 8 relating to the child population shows how the most unhealthy urban areas are located in different locations. In the central part of the city we have the prevailing uncertainty due to a contemporary low probability of social vulnerability, due to the good density of social services and low probability of urban safety climate, caused by the limited availability of public green. In the north, the situation is more critical, due to the high probability vulnerability caused by the distance from social services.

The false color maps, on the one hand spatialize the risk for the vulnerable population, identifying the most critical areas on which urban and territorial planning should take action primarily through climate adaptation actions; on the other

Figure 5a. Maps of indicators of social and exposure vulnerability for elderly.

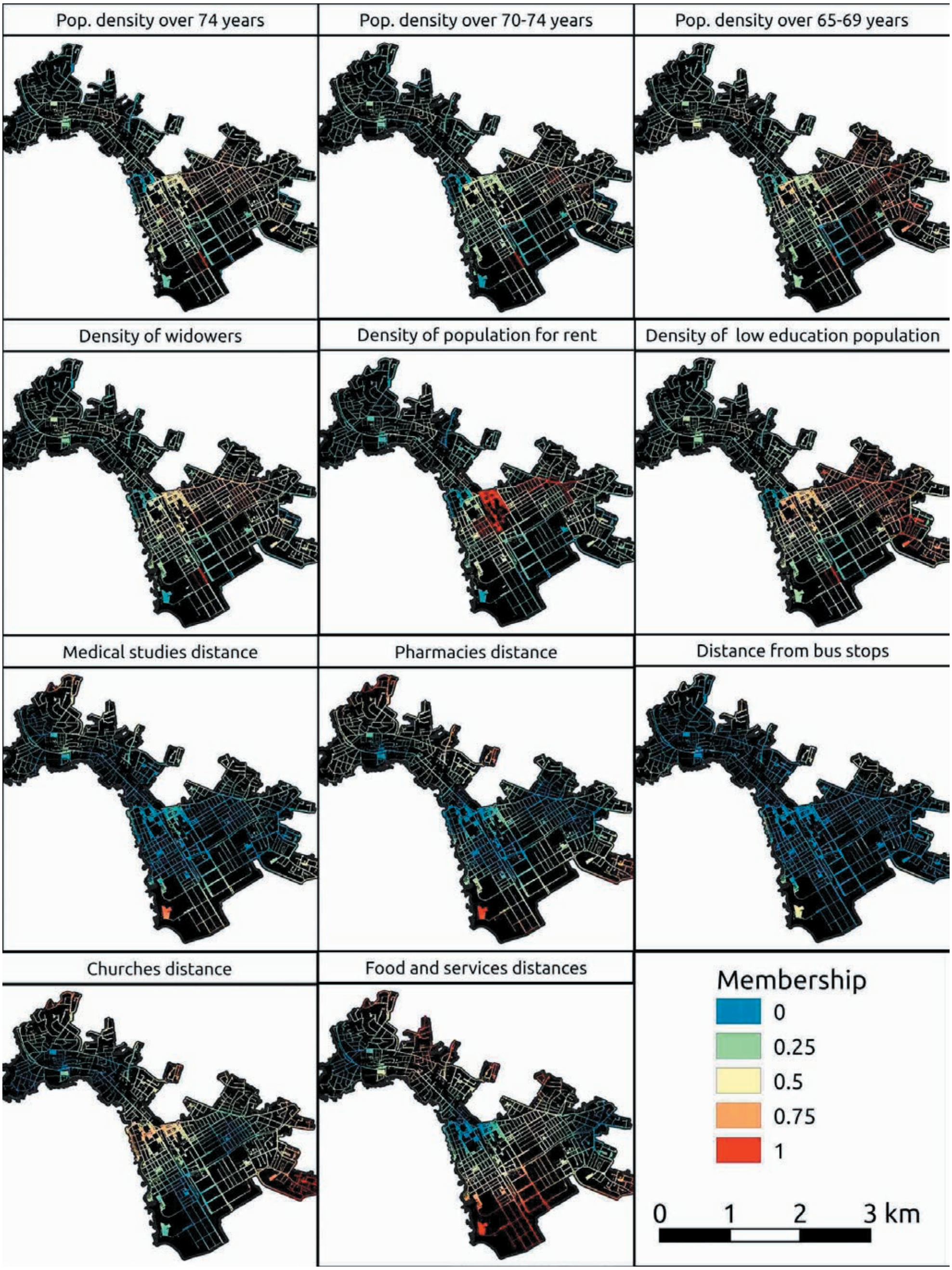
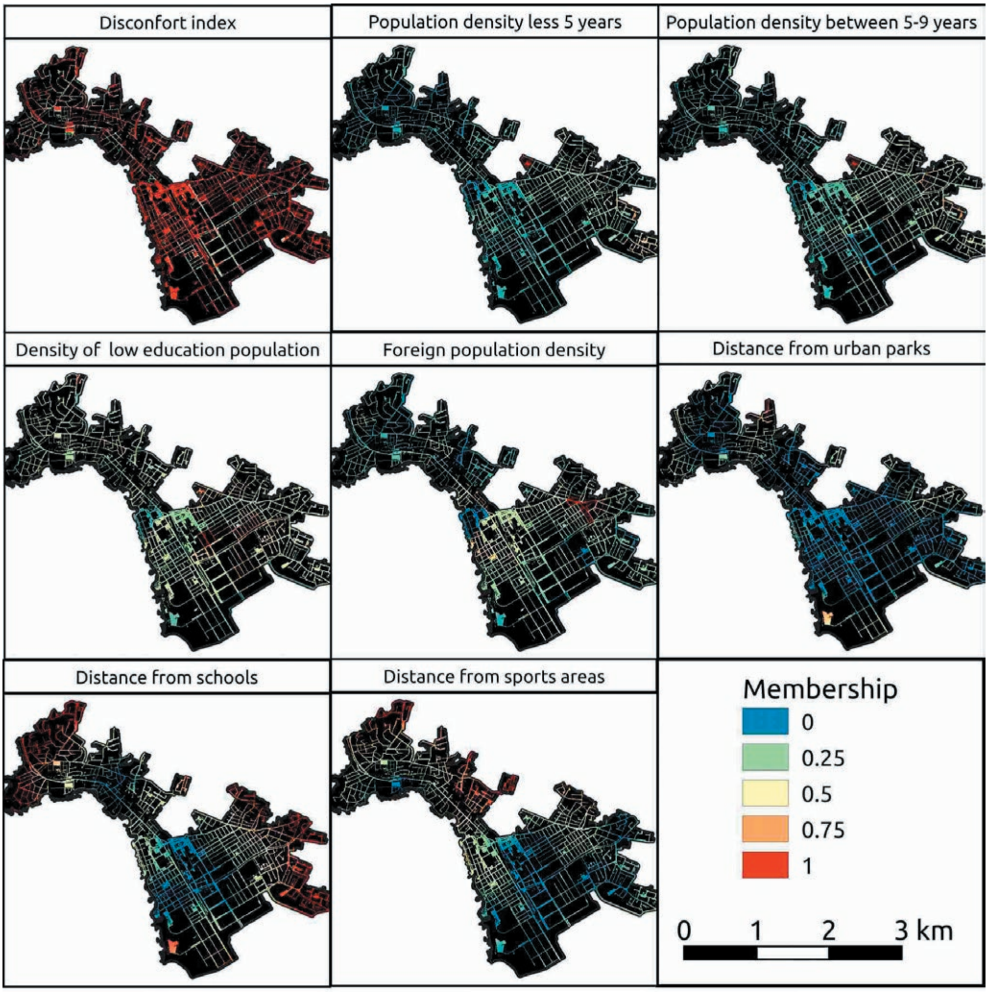


Figure 5b. Maps of indicators of social and exposure vulnerability for children.



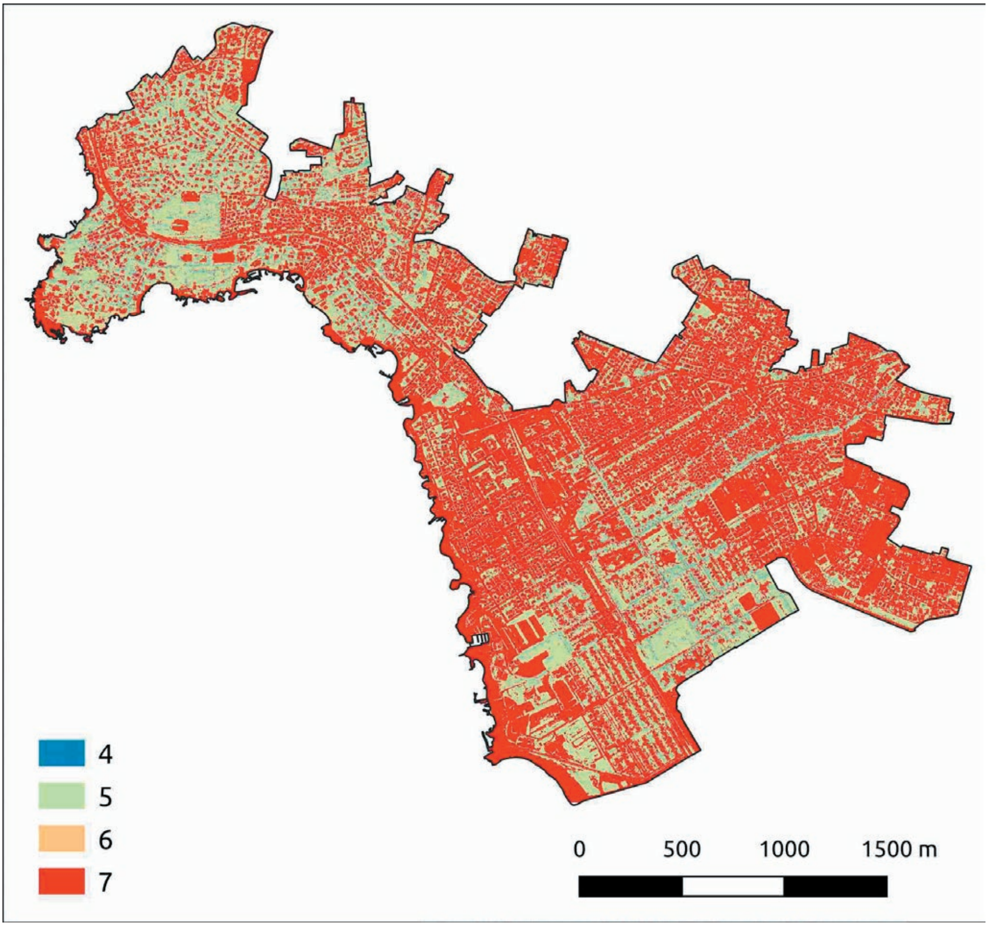
they highlight the positive effect of urban green in reducing the risk to health due to heat waves.

These results help urban and territorial planning to improve the resilience of Rosignano city and ensure a more livable city for all citizens, in particular for the most vulnerable population.

5. Discussion

The main contribution of this work is the identification of high resolution urban areas characterized by the risk of a decrease in well-being and in the social

Figure 6. Comfort index map.

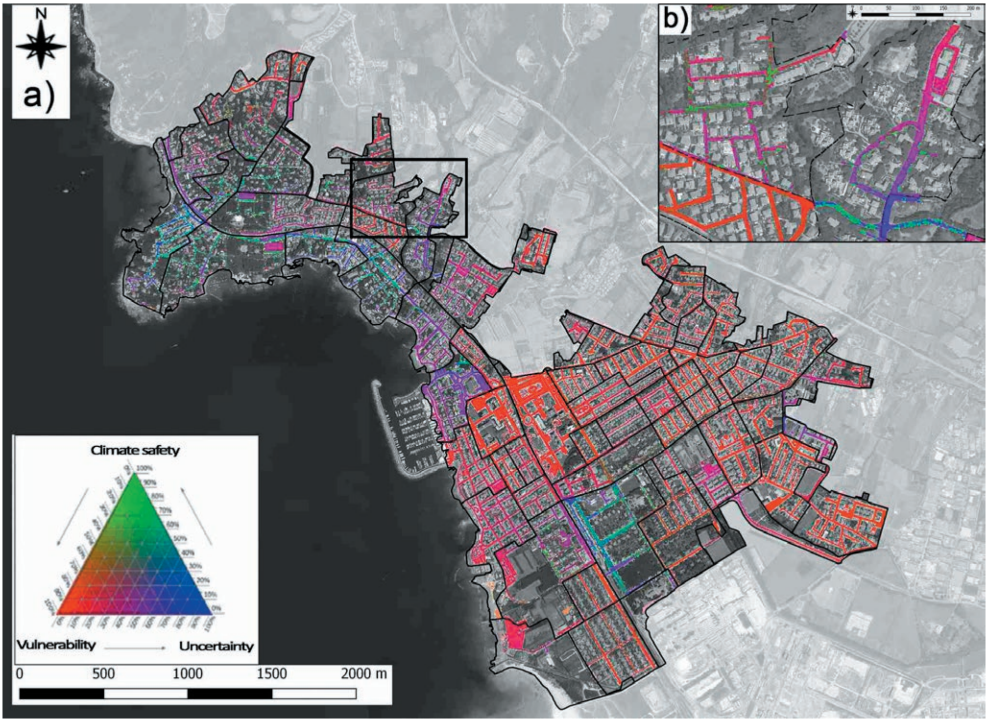


unease in days of extreme heat waves. The work focused on the socially most vulnerable groups i.e. the elderly and children.

The main innovation of this study is represented by the application of the theories of Sen and Nussbaum to the thermoclimatic well-being of urban areas. In according to Krellenberg et al, (2015), Wilhelmi et al. (2010) and Zhang et al. (2018), the capacity approach has in fact allowed to asses two main sources of inequality: the intrinsic factors or those due to the socio-economic conditions of vulnerable individuals and the extrinsic factors due to the characteristics of the urban environment. The most critical factors of environmental inequality were related to the distance from social services and to the temperature of public spaces on critical heat waves days.

Further significant evidence of climate justice is given by the fact that the freshest and livable areas are those with the highest real estate values, forcing

Figure 7. Elderly, false color composition: red = Social Vulnerability, green = Urban Climate Safety, blue = Uncertainty.



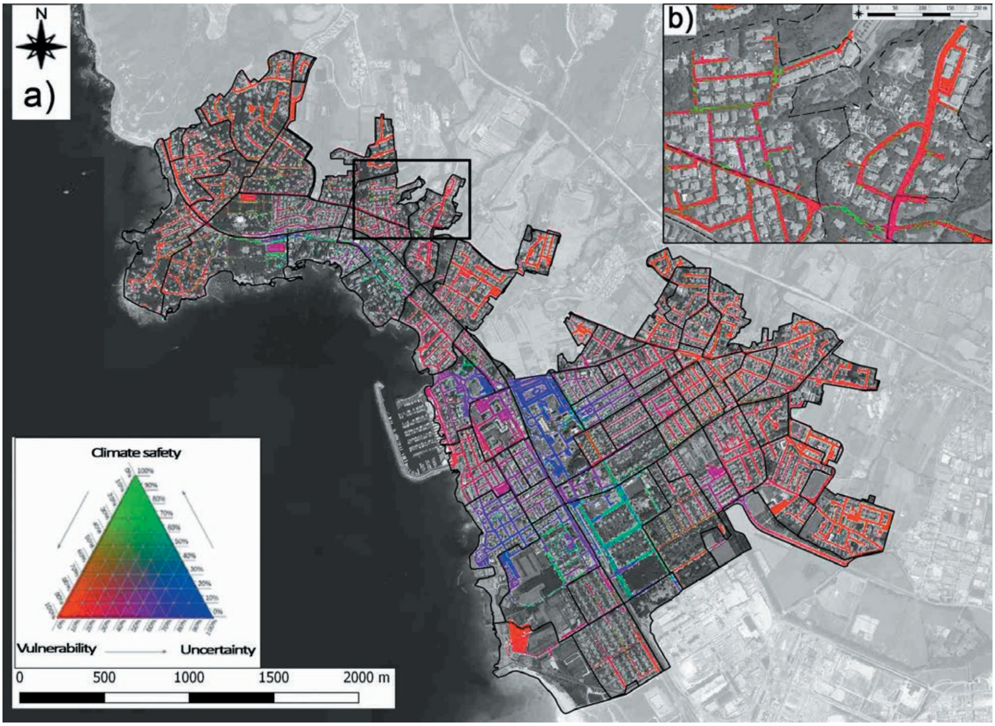
people to pay more for urban well-being. This highlights social disparities in the way individuals are vulnerable to the growing effects of climate change.

This information represents fundamental information to allow effective short-term intervention strategies such as the improvement of the availability of social services and medium/long-term intervention strategies such as the improvement of the albedo of buildings and the design of tree branches and public green areas to be part of the local authorities and urban planners when deciding heat-related health prevention actions at the level of small urban areas.

A second innovative element of the research is the use of an approach based on imprecise probabilities for assessing the reduction of urban well-being caused by extreme weather events. The use of the Dempster Shaffer methodology has allowed to probabilistically treat both the impact of heat waves on health risks for the sensitive population and the effect of the interaction between the different indicators that defined social vulnerability. Besides the possibility to explicitly measure the level of uncertainty allows to highlight the locations in which further investigation will be required.

This study also has some limitations. The social vulnerability of children and the elderly was assessed only through indicators derived from census data. On

Figure 8. Children, false color composition: red = Social Vulnerability, green = Urban Climate Safety, blue = Uncertainty.



the contrary, other socio-demographic and health variables (e.g. physiological adaptation, pre-existing health conditions, use of air conditioning, etc.) are important. Furthermore, information with finer spatial resolution than the census section would be used.

6. Conclusion

This study represents a starting point for identifying areas that require urban adaptation planning strategies. The main project dimensions that have emerged on which to base climate adaptation strategies in urban areas are:

- the increase in efficient public green spaces and corridors;
- the increase of public services;
- the use of high albedo materials;
- the design of new urban spaces with efficient dimensional ratios for temperature mitigation.

To try to limit the increase in temperature in the urban area during the summer season, it is appropriate to increase green surfaces, from large peri-urban parks to street trees, to the smaller interstitial spaces of more structured urban areas. The urban planning tools of the Municipalities must aim decisively to increase the green area and trees in all areas affected by urban transformations, starting from agricultural wedges to large extensive areas. In addition, the "green" furnishings for the redevelopment projects of public spaces must be added, with improved insulation.

Another solution is to approve guidelines for the use of materials that reduce the impact of climate change within neighborhoods. It has now been shown that building materials and choices can significantly aggravate climatic conditions. The floors can constitute up to 45% of the surfaces of a city and are often covered by asphalt and other dark materials that absorb more solar radiation increasing the urban heat island effect. On heatwave days these surfaces can reach very high temperatures, endangering the health of people, in particular the most vulnerable population.

Also as regards the external surfaces of the buildings, including the roofs, it is necessary to consider evaluating the characteristics of roughness, absorption and reflection in the choice of the various materials, to avoid the formation of heat islands mainly due to a diffuse or speculate. Therefore, the interventions must aim to solve this problem by reducing these surfaces, using materials with a high albedo and modulating the spatial configuration to create greater shading solutions.

These adaptation actions and the need for detailed risk assessments for the elderly related to heat within the city are of primary importance to minimize the negative health effects associated with the significant and progressive temperature increases already observed in many cities in because of climate change and urbanization. Future research developments will be as follows. We intend to use the so-called big data from information shared on the internet to verify the relationship between a decrease in well-being and extreme thermoclimatic conditions. We also plan to evaluate the effect of climate change on the capability to live in a safe urban environment using the General Climate Models of the scenarios identified by the International Panel on Climate Change.

References

Abdallah, N. B., Mouhous-Voyneau, N., & Denoeux, T. (2013). Using Dempster-Shafer Theory to model uncertainty in climate change and environmental impact assessments. In *Proceedings of the 16th International Conference on Information Fusion*, IEEE, 2117–2124.

Aminipouri, M., Knudby, A., & Ho, H. C. (2016). Using multiple disparate data sources to map heat vulnerability: Vancouver case study. *The Canadian Geographer/Le Géographe Canadien*, 60(3), 356–368.

Barbierato, E., Bernetti, I., Capecchi, I., & Saragosa, C. (2019). Quantifying the impact of trees on land surface temperature: a downscaling algorithm at city-scale. *European Journal of Remote Sensing*, 52(sup4), 74–83.

Bentabet, L., Zhu, Y. M., Dupuis, O., Kaftandjian, V., Babot, D., & Rombaut, M. (2000). Use of fuzzy clustering for determining mass functions dempster-shafer theory. In *5th International Signal Processing Proceedings, Beijing, China*, 3, 1462–1470.

Bernetti, I., Ciampi, C., Fagarazzi, C., & Sacchelli, S. (2011). The evaluation of forest crop damages due to climate change. An application of Dempster–Shafer method. *Journal of Forest Economics*, 17(3), 285–297.

Caselton, W. F., & Luo, W. (1992). Decision making with imprecise probabilities: Dempster-Shafer theory and application. *Water Resources Research*, 28(12), 3071–3083.

Celati, G., Gattini, L. (1991). *Quando la luna sorrise al lampionaio.* Pisa, Giardini Editore, 21–22.

Celati, G., Gattini, L. (1995). *Sale e Pietra*. Pisa, Giardini Editore, 79.

Chen, S. J., & Hwang, C. L. (1992). Fuzzy multiple attribute decision making methods. In Chen, S. J., & Hwang, C. L. (Eds.). *Fuzzy multiple attribute decision making*. Berlin, Springer, 289–486.

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). A place-based model for understanding community resilience to natural disasters. *Global Environmental Change*, 18(4), 598–606.

Dempster, A. P. (1968a). A generalization of Bayesian inference. *Journal of the Royal Statistical Society*, Series B 30, 205–247.

Dempster, A. P. (1968b). Upper and lower probabilities generalized by a random closed interval. *Annals of Mathematical Statistics,* 39, 957–966.

Dempster, A. P. (1969). Upper and lower probability inference for families of hypotheses with monotone density ratios. *Annals of Mathematical Statistics*, 40, 953–969.

Eisenman, D. P., Wilhalme, H., Tseng, C. H., Chester, M., English, P., Pincetl, S.,& Dhaliwal, S. K. (2016). Heat Death Associations with the built environment, social vulnerability and their interactions with rising temperature. *Health & Place*, 41, 89–99.

Fainstein, S. S. (2014). The just city. *International Journal of Urban Sciences*, 18(1), 1–18.

Fraser, A. M., Chester, M. V., & Eisenman, D. (2018). Strategic locating of refuges for extreme heat events (or heat waves). *Urban Climate*, 25, 109–119.

Fraser, A. M., Chester, M. V., Eisenman, D., Hondula, D. M., Pincetl, S. S., English, P., & Bondank, E. (2017). Household accessibility to heat refuges: residential air conditioning, public cooled space, and walkability. *Environment and Planning B: Urban Analytics and City Science*, 44(6), 1036–1055.

Ghobadi, A., Khosravi, M., & Tavousi, T. (2018). Surveying of heat waves impact on the urban heat islands: case study, the Karaj City in Iran. *Urban Climate*, 24, 600–615.

Givoni, B., Noguchi, M., Saaroni, H., Pochter, O., Yaacov, Y., Feller, N., & Becker, S. (2003). Outdoor comfort research issues. *Energy and Buildings*, 35(1), 77–86.

Hall, J., Fu, G., & Lawry, J. (2007). Imprecise probabilities of climate change: aggregation of fuzzy scenarios and model uncertainties. *Climatic Change*, 81(3-4), 265–281.

Holland, B. (2008). Justice and the environment in Nussbaum's "Capabilities Approach" why sustainable ecological capacity is a meta-capability. *Political Research Quarterly*, 61(2), 319–332.

Hughes, S. (2013). Justice in urban climate change adaptation: criteria and application to Delhi. *Ecology and Society*, 18(4), 48.

Inostroza, L., Palme, M., & de la Barrera, F. (2016). A heat vulnerability index: spatial patterns of exposure, sensitivity and adaptive capacity for Santiago de Chile. *PLOS one*, 11(9), 1–26, e0162464.

Isoard, S., & Winograd, M. (2013). Adaptation in Europe: addressing risks and opportunities from climate change in the context of socio-economic developments. *Publications Office of the European Union*.

James, S. W., & Friel, S. (2015). An integrated approach to identifying and characterising resilient urban food systems to promote population health in a changing climate. *Public Health Nutrition*, 18(13), 2498–2508.

Jean-Baptiste, N., Kuhlicke, C., Kunath, A., & Kabisch, S. (2011). Review and evaluation of existing vulnerability indicators for assessing climate related vulnerability in Africa. UFZ-Bericht, No. 07/2011, Helmholtz-Zentrum für Umweltforschung (UFZ), Leipzig.

Krellenberg, K., Link, F., Welz, J., Barth, K., Harris, J., Irarrázaval, F., & Valenzuela, F. (2015). Approaching urban vulnerability to climate change induced risks in socio-environmentally fragmented areas: the case of Santiago de Chile. UFZ-Bericht, No. 02/2015.

Lindley, S., O'Neill, J., Kandeh, J., Lawson, N., Christian, R., & O'Neill, M. (2011). *Climate change, justice and vulnerability.* York, Joseph Rowntree Foundation, 1–177.

Loughnan, M., Tapper, N., & Phan, T. (2014). Identifying vulnerable populations in subtropical Brisbane, Australia: a guide for heatwave preparedness and health promotion. *ISRN Epidemiology*, 821759.

Luo, W. B., & Caselton, B. (1997). Using Dempster–Shafer theory to represent climate change uncertainties. *Journal of Environmental Management*, 49(1), 73–93.
Méndez-Lázaro, P., Muller-Karger, F. E., Otis, D., McCarthy, M. J., & Rodríguez, E. (2018). A heat vulnerability index to improve urban public health management in San Juan, Puerto Rico. *International Journal of Biometeorology*, 62(5), 709–722.
Meyer, L., Brinkman, S., van Kesteren, L., Leprince-Ringuet, N., and van Boxmeer, F. (2014). IPCC, 2014: climate change 2014: synthesis report. Contribution of Working Groups I. II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.
Morabito, M., Crisci, A., Gioli, B., Gualtieri, G., Toscano, P., Di Stefano, V., & Gensini, G. F. (2015). Urban-hazard risk analysis: mapping of heat-related risks in the elderly in major Italian cities. *PLoS one*, 10(5), e0127277.
Mortensen, J. W., Heaton, M. J., & Wilhelmi, O. V. (2018). Urban heat risk mapping using multiple point patterns in Houston, Texas. *Journal of the Royal Statistical Society: Series C (Applied Statistics)*, 67(1), 83–102.
Nussbaum, M. (2006a). *Frontiers of Justice: Disability, Nationality, Species Membership*. Cambridge, MA, Harvard University Press.
Nussbaum, M. (2006b). Capabilities as fundamental freedoms: sen and social justice. In Kaufman, A., (Ed.). *Capabilities Equality: basic issues and problems*. New York, Routledge. 44–70.
Nussbaum, M., & Sen, A. (1993). *The quality of life*. Oxford, Oxford University Press.
Page, E. A. (2007a). *Climate change, justice and future generations*. Cheltenham, Edward Elgar Publishing.
Page, E. A. (2007b). Intergenerational justice of what: welfare, resources or capabilities?. *Environmental politics*, 16(3), 453–469.
Porębski, S., & Straszecka, E. (2016). Membership functions for fuzzy focal elements. *Archives of Control Sciences*, 26 (3), 395–427
Reid, C. E., O'neill, M. S., Gronlund, C. J., Brines, S. J., Brown, D. G., Diez-Roux, A. V., & Schwartz, J. (2009). Mapping community determinants of heat vulnerability. *Environmental Health Perspectives*, 117(11), 1730–1736.
Robeyns, I. (2005). The capability approach: a theoretical survey. *Journal of Human Development*, 6(1), 93–117.
Robeyns, I. (2016). Capabilitarianism. *Journal of Human Development and Capabilities*, 17(3), 397–414.
Rozbicki, T., & Golaszewski, D. (2003). Analysis of local climate changes in Ursynów in the period 1960–1991 as a result of housing estate development. In Procedings Fifth International Conference on Urban Climate, IAUC and WMO, Vol. 2, 455–458. Lodz, Poland,1–5 September.
Schlosberg, D. (2012). Climate justice and capabilities: s framework for adaptation policy. *Ethics & International Affairs*, 26(4), 445–461.
Sen, A. (1999). Commodities and capabilities. OUP Catalogue. Oxford University Press.
Sen, A. (2014). Development as freedom. In Roberts, T., Hite, A. B., & Chorev, N. (Eds.). *The globalization and development reader: perspectives on development and global change*, 525–548.
Shafer, G. (1967). *A Mathematical Theory of Evidence*. Princeton, N.J., Princeton University Press.
Shafer, G. (1982). Belief functions and parametric models. *Journal of the Royal Statistical Society. Series B*, 44, 322–352.
Theoharatos, G., Pantavou, K., Mavrakis, A., Spanou, A., Katavoutas, G., Efstathiou, P., & Asimakopoulos, D. (2010). Heat waves observed in 2007 in Athens, Greece: synoptic conditions, bioclimatological assessment, air quality levels and health effects. *Environmental Research*, 110(2), 152–161.
Uejio, C. K., Wilhelmi, O. V., Golden, J. S., Mills, D. M., Gulino, S. P., & Samenow, J. P. (2011). Intra-urban societal vulnerability to extreme heat: the role of heat exposure and the built environment, socioeconomics, and neighborhood stability. *Health & Place*, 17(2), 498–507.
Ummenhofer, C. C., & Meehl, G. A. (2017). Extreme weather and climate events with ecological relevance: a review. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372(1723), 20160135.

UNCED (1992). Report of the United Nations conference on environment and development. Rio de Janeiro, Brazil, United Nations Department of Economic and Social Affairs (DESA).
Viccaro, M., Cozzi, M., Fanelli, L., & Romano, S. (2019). Spatial modelling approach to evaluate the economic impacts of climate change on forests at a local scale. *Ecological Indicators*, 106, 105523.
Walley, P. (1991). *Statistical Reasoning with Imprecise Probabilities*. London, Chapman & Hall.
Wilhelmi, O. V., & Hayden, M. H. (2010). Connecting people and place: a new framework for reducing urban vulnerability to extreme heat. *Environmental Research Letters*, 5(1), 014021.
Yager, R. R. (1999). A class of fuzzy measures generated from a Dempster–Shafer belief structure. *International Journal of Intelligent Systems*, 14(12), 1239–1247.
Zhang, W., McManus, P., & Duncan, E. (2018). A raster-based subdividing indicator to map Urban Heat Vulnerability: a case study in Sydney, Australia. *International Journal of Environmental Research and Public Health*, 15(11), 2516.