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Towards a heterogeneous data processing method to support planners in increasing climate resilience: An application on urban heat waves

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The urgency of addressing climate change-induced risks is internationally recognised. However, urban and territorial contexts do not yet appear ready to face this challenge. Based on the state of the art, this research proposes the definition of an innovative method for mapping heterogeneous data to support planners in increasing climate resilience. The application of the research project presented in this paper focuses on heat waves in the urban area of the Municipality of Lamezia Terme (Calabria Region, Italy). Taking into account climatic and non-climatic information, the results are useful for planners to identify priority areas and subsequently define an action plan containing appropriate adaptation measures.

Keywords: urban planning, climate change, adaptation, urban heat waves, Italy

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Introduction

Planners are committed to increasing the liveability of the urban and regional environments (Sheikh & van Ameijde, 2022), holistically addressing (Schirru, 2018; Kramar et al., 2019; Uehara, 2019; Declerck et al., 2023) the complex challenges posed by contemporaneity. Among these, the rapid climate changes require a rethinking of urban and regional development models, aimed at stimulating the resilience of infrastructures and communities (Marschütz et al., 2020). Internationally, climate-related risks pose a major threat to urban safety, infrastructure stability and socio-economic sustainability (Sun et al., 2021). In recent years, the notion of resilience has become highly popular in both research and practice (Wardekker, 2021), firmly entering the discipline of urban planning, which is committed to addressing the vulnerabilities and cities' exposure to present and future hazards, particularly related to climate change effects (Caldarice et al., 2021). In the context of climate change, the concept of resilience is inherently malleable (Wardekker, 2021), sometimes being uncertain and controversial (Taylor & Bhasme, 2021), as it can be framed in different ways, emphasising different problems, causes, and solutions. In general, the most resilient areas are those with the highest levels of adaptive capacity.

According to Zhan-Yun (2021), integrating climate change adaptation goals into spatial planning has become an international mainstream policy. He highlights a number of problems and challenges related to the implementation of effective adaptive planning, linked, for example, to the mismatch between climate change risk assessment and spatial planning scale, the lack of coordination mechanisms of adaptation and mitigation strategies, and the imperfection of technical standards. Although the author refers to the Chinese case, the picture he outlines also appropriately describes the situation in many European countries (Greiving & Fleischhauer, 2016), including Italy. In fact, despite the increasing attention to urban resilience, its implementation at the local scale and the required increasing ambition are still lagging (Caldarice et al., 2021), also due to a lack of dialogue among researchers (the scientific level), policymakers (the normative level) and practitioners (the operational level).

From a regulatory point of view, Italy approved the National Climate Change Adaptation Plan in 2023 to guide the planning of adaptation policies at the national and, above all, regional and local levels, in the short and long term. However, based on a first analysis of the document, this does not seem to provide precise operational guidance in relation to its local implementation, which, however, appears necessary. In fact, currently, only a few Italian cities, and especially large ones, have implemented local climate adaptation plans.

Taking these needs into account, this paper presents some results of a research project funded under the University of Calabria's competitive call—Rectoral Decree 1101/2022 of 29/07/2022. The project aims to increase the climate resilience of infrastructure and communities, alludes to the need to put in place appropriate planning measures to adapt urban and territorial contexts to contain climate change impacts (Cobbinah, 2021), extending this reflection to rural and coastal areas and not only to urban areas. The research activities, also presented during the 18th AESOP Young Academics Conference in Milan in 2024, are divided into three main phases, some of which are partially presented in this paper. The first phase includes the analysis of the state of the art in order to deepen the theories and the main results of existing research in the literature and identify any gaps to be filled. The second phase coincides with the definition of a digital platform to evaluate and map the domains of local risk to climate change (Palermo et al., 2025) and the development of the subsequent action plan containing the abacus of adaptation measures. The third phase refers to the application and validation of the results and consists of testing the research product in local sample contexts. Conceptually, the main reference for the research project is the contribution of the 2022 Intergovernmental Panel on Climate Change (IPCC), which assesses the impacts of climate change and identifies four key risk categories for Europe (Pörtner et al., 2022). The first risk relates to heat waves, which have adverse effects on human life, ecosystems and society, affecting mainly urban areas. Literature studies on climate change predict that global warming will increase the severity, duration, and frequency of heat waves. Therefore, understanding the evolution of the phenomenon is a central issue with high relevance for society (Chitsaz et al., 2023). The second risk relates to agricultural production because changes in climatic events such as temperature and rainfall significantly affect the yield of crops (Malhi et al., 2021). The third risk relates to the scarcity of water resources, which requires a refocus on reliable and sustainable water supplies, especially in arid and semi-arid regions, which are the most water-deprived regions in the world (Shevah, 2015). The fourth risk is induced by increased frequency and intensity of flooding because, also according to Kundzewicz (2005), over time, hydrological variables, such as precipitation, river flow, soil moisture and groundwater levels, display strong spatial and temporal variability.

These four categories constitute the characterising elements of the general climate change risks framework, which is the subject of the theoretical and methodological study published in Palermo & Chieffallo (2024) and briefly described below. However, this paper will refer only to heat wave risk linked to the increase in average temperatures (Beasley et al., 2023; Jeong et al., 2023) and to urban morphology (López-Casado & Fernández-Salinas, 2023; Naserikia et al., 2023; Venerandi et al., 2023). For these reasons, this risk is particularly high in urban areas. Urban planning responses are crucial to improving the capacity of cities and communities to deal with significant temperature variations across seasons (Jeon et al., 2023). To this end, this study proposes the application of the above-mentioned digital platform, which facilitates the integration between climatic and non-climatic information, useful for planners to identify priorities for action in the context of experimentation.

Background: lessons learned from the state of the art

As part of the general research project, to identify the main lines of research (RQ) for the four key risk categories defined by the sixth assessment report of the IPCC (Pörtner et al., 2022), a multiple Systematic Literature Review (SLR) process was conducted to explore quantitatively and qualitatively the state of the art in the period from 2013 to 2023 in the international context. By accessing the Scopus electronic literature database and applying specific inclusion and exclusion criteria for documents, a bibliometric network was extracted (Figure 1) consisting of 2,085 relevant documents (600 relating to heat wave risks, 392 relating to risks for agricultural production, 240 relating to risks of scarcity of water resources and 853 relating to the risks arising from flooding). The analysis of the documents' main information shows a growth rate of scientific production of around 20 %. The selected documents are, on average, signed by 5 authors and have an average of citations per document close to 30.

The data of the bibliometric network were collected and organised to elaborate synthesis results in graphic and tabular form. A Cluster Analysis (CA) technique has been applied to the set of keywords contained in the selected documents. CA is a purely statistical technique of typological research that allows one to interpret the selected literature from a qualitative point of view, identifying homogeneous thematic sub-classes based on different characteristics (Green et al., 1967). In this case, the co-occurrence of keywords is considered to be representative of the contents of the documents. The results allow the generation of research hypotheses on possible latent structures that contribute to the characterisation of the research topic. To this end, the VOSviewer software was used to extract the cluster map with the keywords that co-occur more than 28 times in the Network Visualisation (Figure 2). As anticipated, this paper refers only to the results relating to heat wave risk. This choice is motivated by the increasing frequency and intensity of the phenomenon in urban areas, confirmed by the literature.

RQ(I) «What are the main lines of research related to heat wave risks?»

Timespan 2013:2023	Sources 266	Annual Growth Rate 21.04%
Authors 2839	Authors of single-authored docs 36	Co-Authors per Doc 5.75
Author's Keywords 1584	References 35074	Average citations per Doc 29.7

RQ(II) «What are the main lines of research related to risks for agricultural production?»

Timespan 2013:2023	Sources 201	Annual Growth Rate 25.47%
Authors 1866	Authors of single-authored docs 24	Co-Authors per Doc 5.12
Author's Keywords 1286	References 25431	Average citations per Doc 32.29

RQ(III) «What are the main lines of research related to the risks of water scarcity?»

Timespan 2013:2023	Sources 140	Annual Growth Rate 19.95%
Authors 1083	Authors of single-authored docs 14	Co-Authors per Doc 4.85
Author's Keywords 832	References 16513	Average citations per Doc 28.48

RQ(IV) «What are the main lines of research related to the risks produced by floods?»

Timespan 2013:2023	Sources 302	Annual Growth Rate 24.03%
Authors 3633	Authors of single-authored docs 38	Co-Authors per Doc 4.94
Author's Keywords 2463	References 51792	Average citations per Doc 22.79

Figure 1. *Main information on SLR documents. Source: author's elaboration of Bibliometrix results*

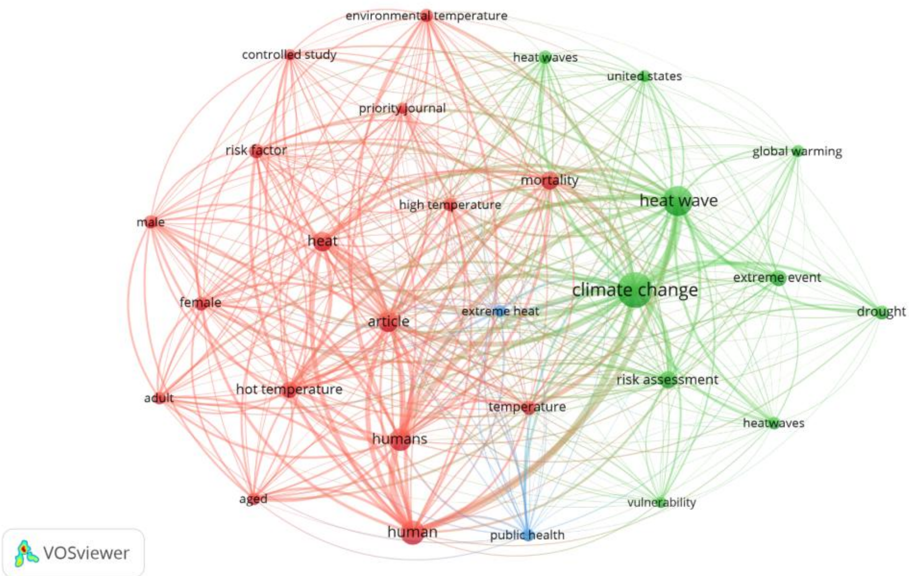

Figure 2. *Network Visualisation related to RQ(I). Source: author's elaboration of VOSviewer results*

Three thematic clusters of literature about heat waves emerge from the bibliometric network. They are characterised by different colours. Cluster 1 (in red) concerns climate-related risks' environmental characterisation. Cluster 2 (in green) concerns heat wave assessment tools. Cluster 3 (in blue) concerns the effects of extreme heat on public health.

Documents of cluster 1 highlight how some elements (such as the orographic complexity of the territory) can profoundly influence the rainfall regime and the change in temperatures during the year. To these, additional "environmental" factors related to land use are added, such as the layout of buildings and other structures (Demdoum et al., 2023) within the urbanised area, and the presence of vegetation, which has mitigating effects on the surface temperature (Ossola et al., 2021).

The most recent literature of cluster 2 contains different risk assessment methods that mainly refer to temperature and humidity (Arshad et al., 2020; Cho, 2020; Cotlier & Jimenez, 2022; Wu et al., 2022; Dayan et al., 2023; Quesada-Ganuza et al., 2023), which are among the main variables influencing environmental stress (Infusino et al., 2021). The expectation that climate change can further exacerbate extreme weather events such as heat waves is of primary concern to policymakers and scientists (Vanderplanken et al., 2021). For this reason, urban planning instruments require a strategic view that enables the integration of climate change variables within ordinary knowledge frameworks.

Finally, considering cluster 3, the effects of extreme heat waves on health appear related to many interrelated factors. The extreme climatic events that have occurred in recent years show the inadequacy of cities in facing the changes (Bassolino & Verde, 2023), which seriously affect health and social systems and threaten ecological diversity worldwide (Klingelhöfer et al., 2023). Urban heat islands are frequently formed. This is a microclimatic phenomenon that especially affects urban areas, resulting in significant temperature increases in the local microclimate that can amplify heat waves, causing thermal discomfort and a reduction in the levels of quality of life (Leal Filho et al., 2021). Literature researches appear to be mainly oriented towards identifying the most vulnerable population, including the elderly, children and fragile subjects suffering from cardiovascular and respiratory diseases. Identifying the population and locations that are under high risk is important in urban planning and design policy making as well as health interventions (Cheng et al., 2021).

From a general point of view, the deepening of the clusters related to the other three risk categories defined by Pörtner (2022), not covered by this paper, has revealed the presence of more or less strong correlations with environmental characteristics, social, and economic aspects associated with urban, rural and coastal areas. Heat wave risks are a priority issue in urban areas, risks to agricultural production and water scarcity are important in rural areas, and flood risks are crucial for coastal areas. This result represents the starting point for the definition of the research product, which cannot consider the risk categories separately but must be oriented towards their integration. Selected literature has highlighted the existence of sector studies aimed at individual risk categories conducted by specialists (Al-Omari et al., 2024; Benami et al., 2021; Dubey et al., 2021; Huang et al., 2024; Sun et al., 2022). For this reason, a single multi-risk framework was defined in the research project, which is easily applicable by urban and regional planners. The framework still allows detailed analyses to be carried out on individual risk categories referring to specific areas of study. In this regard, this paper offers an in-depth analysis of heat waves which particularly affect urban areas.

Data and methods

The general research project aims to fill a specific gap in the literature, which is the lack of an integrated and operational tool to support planning activities aimed at increasing climate resilience by intervening as a priority in the most vulnerable sites. To this end, vulnerability is the component of climate risk on which attention is focused. According to the sixth assessment report of the IPCC (Pörtner et al., 2022), vulnerability represents the result of the interaction between climate change sensitivity and the adaptive capacity of a system or region. Based on evidence provided by the SLR, this research proposes a heterogeneous processing method for data acquired, including climatic and non-climatic information relevant for spatial planning (Daniels et al., 2020), to fill the most relevant decision-making needs. In particular, climatic information describes the component of sensitivity, while non-climatic information refers to the adaptive capacity. The aim is to integrate this information into the digital platform for assessing local climatic vulnerability, creating charts, tables, and spatial mapping of data.

As anticipated, this paper focuses on the phenomenon of heat waves, which is among the most relevant extreme climatic events due to the effects on society, agriculture and the environment (Molina et al., 2020). In recent decades, unprecedented extreme summer heat waves have occurred in Europe, and they have exhibited an increasing trend since the 1970s (Zhang et al., 2020). Similar weather conditions have also affected Italy (Fontana et al., 2015), with particularly intense effects in urban areas, but also in rural areas, where they negatively affected agricultural production (Di Blasi et al., 2023).

As part of the general climate change risks framework (Figure 3), climatic and non-climatic information for the development of the digital platform for assessing local climatic vulnerability with respect to heat waves is explained below, including technical definitions and descriptions.

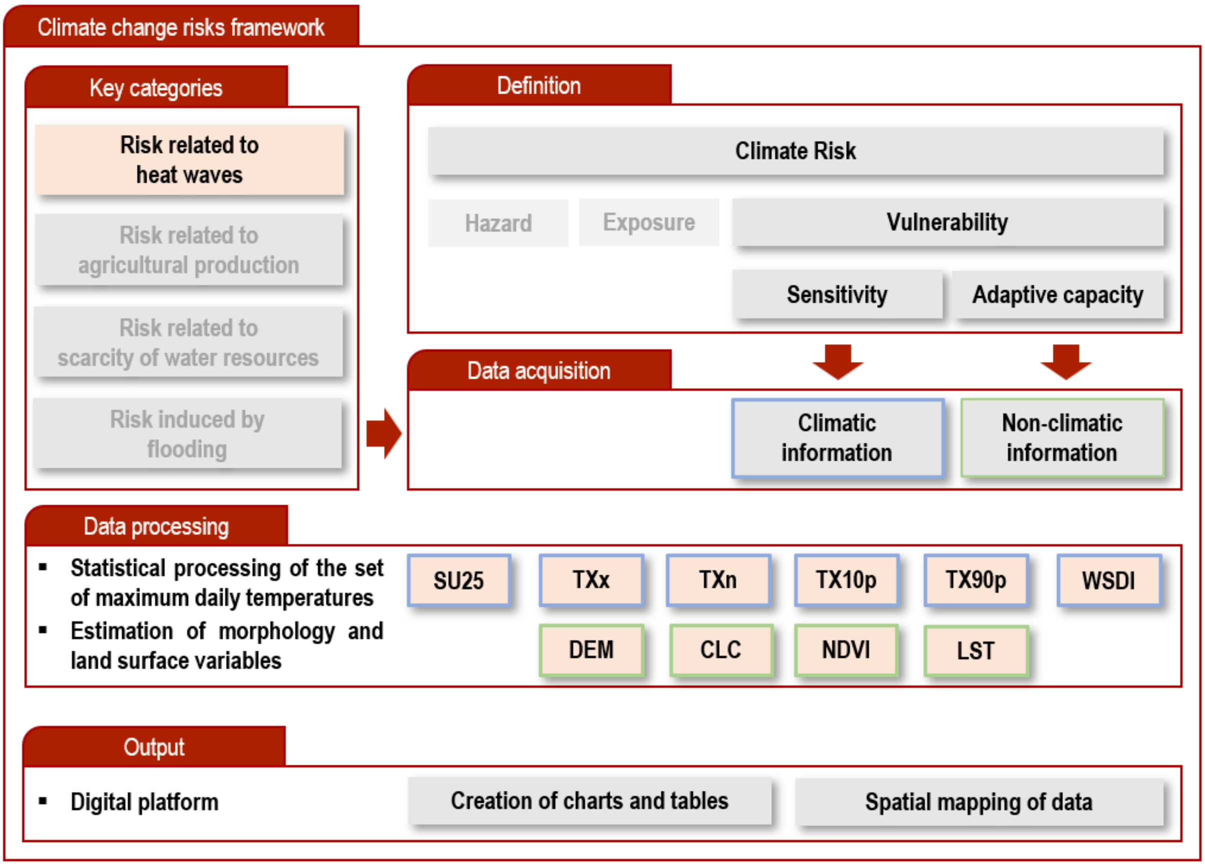

Figure 3. *Diagram of the general climate change risks framework with operational workflow (data acquisition, data processing and output) related to heat waves. Source: author's elaboration*

Climatic information consists of indices useful in describing changes in the intensity, frequency and duration of temperature (Peterson et al., 2001; Zuccaro & Leone, 2021). Climate is an abstraction obtained by statistically processing the set of meteorological variables in order to develop appropriate climate indices (Mariani, 2006). These indices are recommended by the ccl/CLIVAR/JCOMM Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) and are identified among the most representative of the Italian climate (Francini et al., 2020), also by the National Institute for Environmental Protection and Research (called ISPRA). The research has identified the following indices to characterise the observed climate trends (Palermo et al., 2025):

- SU25, the annual count of days when the daily maximum is above 25 °C;
- TXx, the annual maximum value of daily maximum temperature;
- TXn, the annual minimum value of daily maximum temperature;
- TX10p, the annual percentage of cold days (a cold day occurs when the temperature is less than the 10th percentile of the daily annual series);
- TX90p, the annual percentage of hot days (a hot day occurs when the temperature is greater than the 90th percentile of the daily annual series);
- WSDI, the duration of a warm spell (a "warm spell" is defined as at least 6 consecutive days where the daily maximum temperature exceeds the 90th percentile of the daily annual series).

SU25, TX10p and TX90p are threshold indices. TXx and TXn are absolute indices. WSDI is a duration index. These indices allow one to trace the local climate profile of the context of interest, based on the acquisition of the time series of the maximum daily temperatures recorded by monitoring stations equipped with a thermometer. The indices can be calculated for each year of observation according to their definitions.

This information is then compared with non-climatic information. Among these, land cover data recorded by Landsat satellite images (Pappalardo et al., 2023) are very important, as they allow for the calculation of the Normalised Difference Vegetation Index (NDVI) and the estimation of Land Surface Temperature (LST) according to the formulations of Yuan & Bauer (2007) and Stathopoulou & Cartalis (2007). The NDVI index measures the vigour and density of vegetation. The LST index represents the temperature of the Earth's surface. At this stage of the research, the outputs refer to individual indices, as the definition of the synthesis procedure useful for developing the vulnerability mapping is being validated.

Results

The research identifies the Municipality of Lamezia Terme (Calabria Region, Italy) as a case study, in order to investigate a representative context of urban, rural and coastal areas. Focusing on heat waves, the study area coincides with the urban area identified in Figure 4. This study area hosts about 78 % of the entire municipal population in a territory that extends for 1,375 ha (8.6 % of the municipal area) with an altitude between 100 and 340 m above sea level.

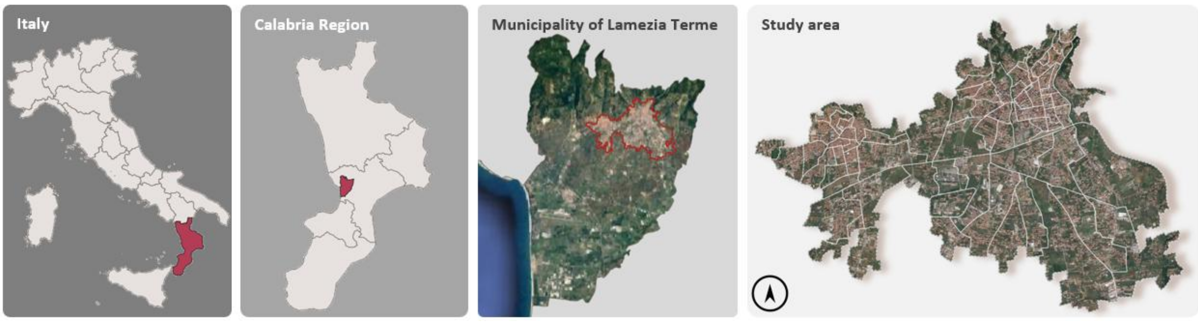

Figure 4. *Location of the study area. Source: author's elaboration*

Climatic information

Climatic information is compiled on the basis of official data measured over a 10-year time span. These data are provided by the Regional Environment Agency (called ARPACAL) and consist of the maximum daily temperatures (Figure 5) recorded from 2014 to 2023 by the ARPACAL station number 2940 called "Nicastro-Bella", active in remote control and located near the study area.

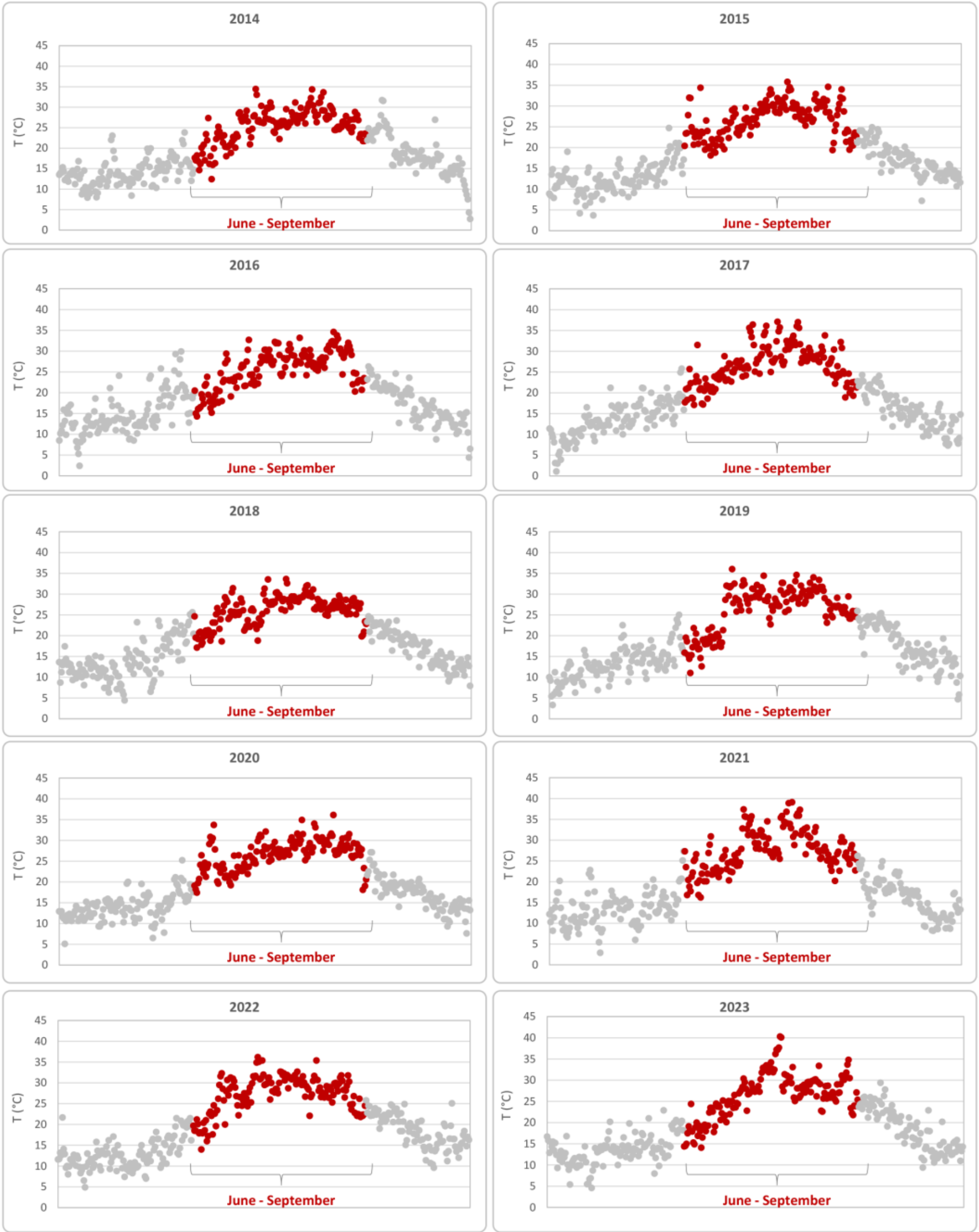

Figure 5. *Annual graphs of the time series of maximum daily temperatures. Source: author's elaboration of ARPACAL data*

Table 1 contains the climatic information obtained by statistically processing the time series of maximum daily temperatures.

***Table 1.** Climatic information. Source: Author's elaboration*

ID	Unit of measure	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
SU25	Days	105	94	97	95	109	111	111	112	115	108
TXx	°C	34.4	35.8	34.6	37.1	33.6	36	36.1	39.1	36.2	40.3
TXn	°C	4.3	3.7	2.4	1.1	4.4	3.3	5.1	2.9	4.9	4.6
TX10p	%	9.8	9.8	9.8	9.8	9.6	9.6	9.6	9.3	9.6	9.6
TX90p	%	10.1	9.6	10.1	9.8	10.1	11.5	9.8	9.8	9.8	9.6
WSDI	Days	14	0	19	20	13	0	8	30	16	27

Non-climatic information

Further analysis of the area yielded non-climatic information. The main results are shown in Figure 6.

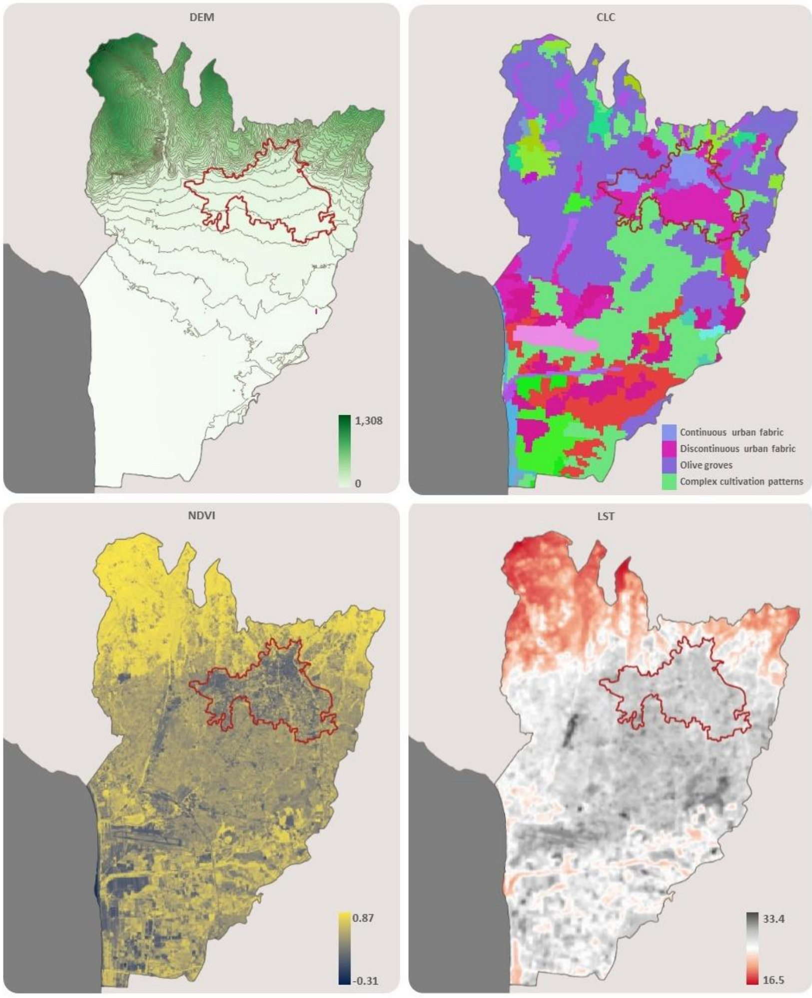

***Figure 6.** Mapping of non-climatic information. Source: author's elaboration*

The non-climatic information was obtained in a Geographic Information Systems (GIS) environment and concerns four factors. The first factor is the orographic profile of the territory,

reconstructed through the Digital Elevation Model (DEM), with a regular grid at a spatial resolution of 5 meters, from which it was possible to digitise the contour lines in vector format by setting the desired spatial range.
The second factor is land use, analysed using data from the Corine Land Cover (CLC) programme. This classification is useful because urbanisation has been contributing to the intensification of urban heat islands (Hellings & Rienow, 2021). The third factor coincides with the Normalised Difference Vegetation Index (NDVI), one of the most widely used vegetation indices in the literature, that effectively illustrates the spatial distribution and growth status of vegetation (Spruce et al., 2011; Wang et al., 2023). Finally, the last factor coincides with the Land Surface Temperature (LST) that fluctuates more and more rapidly, causing climate change and degradation of human life on a local-global scale (Sarif et al., 2022). The NDVI and LST factors were mapped by processing satellite images for bands 4, 5 and 10 of Landsat 9, taken on 27 August 2023, when the ARPACAL station “Nicastro-Bella” recorded the highest temperature of August.

Discussion and conclusion

This research has addressed heat wave risk as one of the climate change risk categories (Pörtner, 2022), with a focus on urban areas. However, as anticipated, the overall research product will be oriented towards the integration of the four risk categories, also extending the analysis to rural and coastal areas. Therefore, the results presented here relate only to some of the elements that will flow into the digital platform for the assessment of vulnerability to climate change and the development of related mapping. The results represent some of the climatic and non-climatic information relevant for decisions in relation to heat waves or the identification of specific adaptation measures.

The climatic information has been obtained by elaborating the time series of maximum temperatures, of which the descriptive statistics are reported below (Table 2), useful for the discussion of the results.

Table 2. *Descriptive statistics on climatic information. Source: author’s elaboration*

Index	SU25	TXx	TXn	TX10p	TX90p	WSDI
Mean	103.9	36.2	3.5	9.6	10.0	13.8
Standard error	2.4	0.5	0.4	0.1	0.1	2.9
Median	106.5	35.9	3.7	9.6	9.8	15.0
Mode	111.0	35.8	3.7	9.8	9.8	0.0
Standard deviation	8.3	1.9	1.3	0.2	0.5	10.2
Sample variance	69.7	3.6	1.6	0.0	0.3	103.6
Kurtosis	-1.4	1.0	-0.5	0.0	8.6	-0.9
Asymmetry	-0.4	1.1	-0.6	-0.9	2.8	-0.1
Range	25	6.7	4	0.5	1.9	30
Minimum	90	33.6	1.1	9.3	9.6	0
Maximum	115	40.3	5.1	9.8	11.5	30

The highest temperatures are recorded during the extended summer period, from June to September (the highest temperature ever in the reference period is 40.3 °C, recorded on 24 July 2023), with episodes of intense and prolonged heat increasingly frequent. The periods of heat are identified by the WSDI index, which expresses the duration, in number of days, of periods consisting of at least 6 consecutive days in which the temperature is greater than that associated with the 90th percentile annual series. In the climatological period considered, on average, these periods last 13 days, but the results are very variable. In fact, while in some years there are no warm periods (2015, 2019), more recently, such periods had values much higher than the average value, with peaks of 30 days in 2021 and 27 days in 2023. Similar trends are also recorded for other indices, such as SU25, which expresses the number of days per year in which the temperature exceeds 25°C, reaching its peak in 2022, equal to 115 days. With regard to climatic information, future development of the research plan will extend the climatic reference period by analysing the average values of climatic quantities over a longer period of time, equal to thirty years. In addition, it is also intended to take into account further time series, namely those relating to minimum temperatures and precipitation, in order to derive appropriate representative indices.

Compared to non-climatic information, the information presented in the paper represents only some of the factors that affect the urban microclimate, contributing to the phenomenon of heat island in areas with high soil consumption and low tree cover. Future developments of the research foresee defining analytical activities of synthesis and aggregation of the aforementioned factors, to offer an integrated vision of the entire informative patrimony and provide more useful information to support the planning choices.

Indeed, the elaboration of the information proposed in this study could provide a guideline for building climate-resilient infrastructures and communities. In addition to identifying priority areas for action, the results help to define an action plan containing appropriate adaptation measures. The results obtained considering individual parameters can support administrations in defining intervention priorities and can also be easily integrated into existing GIS. Specifically, the research aims to promote climate-adaptive planning in local contexts, starting with the identification of the most vulnerable areas where climate-effective interventions can be supported, including the morphological reconfiguration of urban spaces aimed at, for example, increasing tree cover and removing high-emissivity surfaces. For example, in this specific case, the following actions are required on the settlement system:

- promoting the containment of soil sealing;
- supporting the development of green infrastructure;
- indicating requirements for materials that limit the heat absorption of buildings and soils;
- starting experimental building adaptation.

The methodological approach resulting from the study of literature described in this paper, albeit synthetically and still in progress, meets the ambition of the research to define a scalable framework that can guide the planner in choosing the most appropriate adaptation actions according to the characteristics of the context. This goal is essential to efficiently plan and implement resilient contexts, avoiding irreversible environmental, economic, and social problems in the foreseeable future.

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