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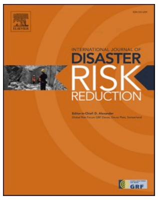

An integrated assessment of heat hazard, vulnerability, and accessibility to climate shelter networks for identifying urban adaptation priority areas in Andalusia (Spain)

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ABSTRACT

Climate change is intensifying the effects of extreme heat, particularly in urban environments, posing a risk to public health and disproportionately affecting vulnerable populations. Urban climate shelters have emerged as a short-term adaptation measure, yet their deployment is often based on existing infrastructure and does not systematically respond to spatial patterns of heat hazard or social vulnerability. This study develops an integrated framework to assess the accessibility of climate shelter networks while explicitly accounting for territorial variations in hazard and population vulnerability. The approach combines hazards and vulnerability indices with network-based accessibility analysis to identify priority areas for intervention and urban adaptation planning. Applied to Andalusia (southern Spain), a Mediterranean climate change hotspot, the results reveal significant spatial mismatches between heat hazard and access to climate shelters, highlighting areas of compounded vulnerability. Results show that more than 50% of the resident population in Andalusia live in high or very high priority areas, considering hazard, vulnerability, and accessibility to climate shelters. The study provides a transferable, equity-oriented methodology to support disaster risk reduction and climate adaptation strategies under increasing heat stress.

1. Introduction

Mortality and morbidity associated with rising temperatures and extreme heat are among the main risks faced by Europe [1,2]. In recent decades, an increase in average temperatures and in the frequency, intensity, and duration of extreme events such as heat waves and tropical nights is also linked to several non-fatal health problems, including heat stroke, dehydration, loss of work productivity, and decreased learning [3–5]. In urban environments, these impacts are further intensified by the urban heat island effects, which amplify nocturnal and daytime heat stress and prolong exposure during extreme events [6,7].

The impacts of extreme heat are unevenly distributed across populations. Ongoing urbanization processes and demographic ageing

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are expected to exacerbate future heat-related risk, increasing both exposure and sensitivity in urban areas [8], people with chronic conditions [9–11], those with low socioeconomic status [12,13], and people who are isolated [13]. These patterns underline that heat risk is not solely a function of climatic conditions but is deeply shaped by demographic and socioeconomic factors that condition people's capacity to cope with extreme temperatures. Urban adaptation to rising temperatures and extreme heat has therefore become a priority challenge. Exposure to cool environments during heat episodes has been shown to significantly reduce heat stress and related health risk [14,15], making access to cooling spaces a key short-term adaptation strategy. In this context, urban climate shelters have emerged as an increasingly common response. Climate shelters are accessible indoor or outdoor spaces—such as air-conditioned buildings or shaded areas—that provide thermally comfortable and safe conditions during extreme heat events, while continuing to serve their original functions [16–19].

Despite their growing relevance, climate shelter networks are not always distributed equitably. Since they are typically based on pre-existing urban infrastructure, their spatial configuration often reflects historical planning decisions rather than current patterns of heat risk or social vulnerability. From a climate justice perspective, adaptation strategies should not only aim to reduce overall risk but also to address structural inequalities in exposure and access to protective resources. Recent policy frameworks at the European level stress that vulnerable groups should play a central role in adaptation planning and in the provision of climate services. However, empirical studies have shown that the needs of elderly and low-income populations are frequently insufficiently met in existing climate shelter networks [19–21].

Extreme heat intersects with pre-existing socio-spatial inequalities, processes of environmental racism, and dynamics of climate gentrification, leading to uneven distributions of cooling infrastructure and green spaces within cities [22–25]. As a result, populations most exposed and most vulnerable to heat are often those with the least access to cooling resources. Recent assessments emphasize the need for “fair adaptation” approaches that systematically evaluate who benefits from heat adaptation measures and who is left behind [1,26]. In this sense, climate shelter networks raise critical questions regarding accessibility, equity, and the right to the city under conditions of extreme heat.

Although the accessibility of climate shelters has increasingly been addressed in the context of heat adaptation planning, existing studies tend to evaluate accessibility primarily in relation to socio-demographic vulnerability or population distribution [20,21]. In parallel, a substantial body of literature has mapped extreme heat hazard and exposure using indicators such as urban heat island intensity or land surface temperature [27,28]. However, these two bodies of literature largely remain disconnected. As a result, planning practice still lacks an operational, equity-oriented tool to prioritize where climate shelters are most needed. As pointed out by [29], significant knowledge gaps persist, underscoring the urgent need for interdisciplinary research to inform climate adaptation strategies. To date, there is a notable lack of studies that explicitly integrate network-based accessibility to climate shelters with spatially explicit heat-hazard and vulnerability assessments in a unified prioritization framework. As a result, current approaches often fail to identify territorial mismatches between areas experiencing the most severe thermal and vulnerable conditions and the actual reachability of cooling resources, limiting their usefulness for operational heat-risk adaptation planning.

The objective of this study is to develop an integrated framework to assess the accessibility of climate shelter networks as a short-term adaptation measure to extreme heat, explicitly accounting for territorial needs derived from the spatial distribution of heat hazard and population vulnerability. The approach first constructs hazard and vulnerability indices, then designs a potential network of urban climate shelters based on existing facilities and evaluates pedestrian accessibility using network analysis. Accessibility, hazard, and vulnerability are subsequently combined through prioritization matrices to identify areas where high-risk populations face limited access to shelters, thereby delineating priority areas for targeted urban adaptation interventions. By integrating these dimensions, the study advances current approaches to heat adaptation planning and contributes to more equity-oriented, risk-informed disaster risk reduction strategies.

The analysis is applied to Andalusia (southern Spain), a region located within the Mediterranean basin, which has been widely identified as a climate change “hot spot” due to the marked increase in temperatures observed in recent decades [1,2,30–32]. In the Mediterranean region, and particularly in the Iberian Peninsula, extreme heat events are expected to become more frequent, intense, and prolonged in the coming years [33–35]. In Spain, several studies have documented a significant rise in tropical nights, especially in Mediterranean and Cantabrian coastal areas, not only in terms of frequency and intensity but also in their seasonal extension, with shifts in their onset and end dates since the mid-1970s [36–39]. Despite its high exposure and vulnerability to extreme heat, Andalusia currently lacks formal initiatives aimed at developing climate shelter networks [40], making it a particularly relevant case study for evaluating accessibility-based, risk-informed adaptation strategies.

2. Case study

Andalusia is a region located in southern Spain. With an area of 87,597 km^2, it has 8,631,862 inhabitants, which represents 17.8% of the Spanish population [41]. Its structure is polycentric and highly heterogeneous, organized around eight medium-sized provincial capitals, presenting significant internal differences. While provinces such as Seville, Málaga, Córdoba and Granada have large metropolitan areas and dense urban conurbations, others such as Jaén, Huelva, Cádiz and Almería have a more dispersed pattern, with mainly small and medium-sized municipalities. These eight provinces are divided into 785 municipalities, responsible for urban planning, civil protection, and climate change adaptation. This system is reinforced by recent urban growth, especially in coastal areas such as the Regional Center of Bahía de Cádiz-Jerez, the Málaga coastal axis, and the western area of Almería, where the growth of low-density housing developments has in many cases exceeded the capacity for planning and provision of public services [42]. The coastal-inland difference is also significant: while the coastal strips have a higher concentration of population and urbanization, with high density in areas such as the Málaga coastline (presenting a continuous urban conurbation), the inland areas, especially in mountainous or agricultural regions, maintain a more rural and dispersed structure. In demographic terms, 82.3% of the population lives in urban environments or clusters and only 17.7% in rural environments [43]. Andalusia's per capita income is significantly below the national average. According to the 2025 State of Poverty in Andalusia report, the regional average is 11,719 €, roughly 2300 € less than Spain's national average, ranking Andalusia among the lowest in the country. Furthermore, the territorial distribution of income highlights significant internal heterogeneity: over 80% of Andalusian municipalities fall into the lowest national income quartile, compared to much higher proportions in wealthier regions such as the Basque Country [41]. Fig. 1 shows the location and population density distribution among Andalusia and their eight provinces.

Andalusia is particularly vulnerable to the effects of climate change. A trend is expected towards a warmer climate with more intense extreme events throughout the 21st century. Between 1985 and 2014, this region recorded an average of 3 days of extreme heat (over 40 °C) and 8 tropical nights (nighttime temperatures above 25 °C), with an average temperature of 15.9 °C. For the period 2015-2040, the average temperature is estimated to be 16.7 °C, with 5 days of extreme heat and 15 tropical nights. For 2041-2070, the forecasts are even worse: the average temperature is likely to rise to 19 °C, with 13 days of extreme heat and 34 tropical nights. Between 2071 and 2100, the situation might be critical, with 24 days of extreme heat, 56 tropical nights, and an average annual temperature of 20.8 °C [44]. The highest increase in average temperature and number of tropical nights is concentrated on the Mediterranean coast and in the Guadalquivir Valley, while the increase in extreme heat days is particularly localized inland, especially in the Guadalquivir Valley and the north of the region. In contrast, the coastline is less affected by this last variable, which could be related to the buffering influence of the sea.

3. Methodology

The methodology of this study is structured as a sequence of interrelated analytical phases, designed to identify priority areas for territorial planning of climate shelter networks in response to heat-related risk. The approach integrates the analysis of heat hazard, socioeconomic vulnerability, and spatial accessibility to climate shelters within a coherent spatial framework that enables their joint and comparative assessment.

3.1. Heat hazard assessment

The hazard assessment is based on the physical characteristics of extreme heat events, including intensity, duration, and frequency, which together have been shown to more comprehensively describe extreme heat hazard than single metrics. Heatwave duration (days), reflecting the temporal persistence of extreme temperatures while maximum temperature intensity (°C), capturing the severity of heat peaks. To characterize extreme heat risk more accurately, this study incorporates the number of days exceeding 40 °C in addition to conventional heatwave metrics. This is because previous research has shown that mortality-based (health) and meteorological definitions of heatwaves can differ substantially, indicating that simple percentile-based thresholds alone may not capture the full impact of extreme temperatures on human health [45]. Thus, the annual number of days above 40 °C is used as a supplementary indicator of severe heat stress. The data for the different variables were obtained from [46]. Specifically, projections of the Shared

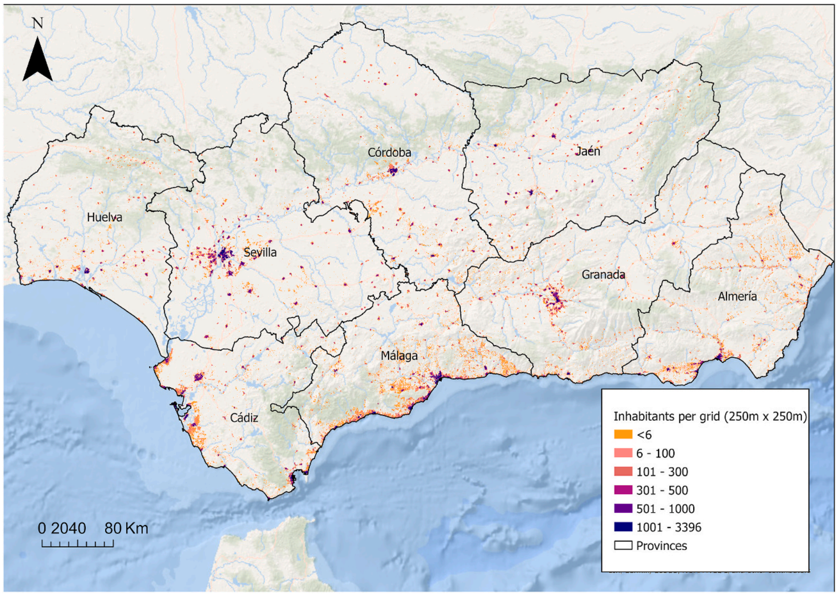

Fig. 1. Location of the case study and population density (inhabitants per 250 × 250m grid)
Source: Compiled by the authors from IECA (2024).

Socioeconomic Pathways (SSP-3-7.5), derived from the Sixth Assessment IPCC Report and regionalized for Andalusia for the 2015–2040 scenario, were used.

Each variable was represented as gridded data. Each raster layer is normalized to a 0–1 scale and then integrated into a composite hazard index. The resulting composite heat hazard index is subsequently classified into five hazard classes—very low, low, medium, high, and very high—using ordinal thresholds to facilitate interpretation and comparison. These hazard classes are then spatially overlaid with the statistical population grid, and each population cell is assigned to a hazard class according to its geographic location within the corresponding hazard zones. This procedure enables the direct linkage between levels of heat hazard and the resident population at the grid-cell scale, providing a consistent spatial basis for subsequent analyses that integrate hazard with vulnerability and accessibility.

3.2. *Vulnerability assessment*

To characterize vulnerability, two main socio-demographic factors were considered: the population aged over 65, representing age-related physiological sensitivity to heat, and average income. In the Spanish context, this heightened vulnerability is consistently reflected in the MoMo (Daily Mortality Monitoring System) indicator, which provides robust empirical evidence of the relationship between extreme temperatures and excess mortality. MoMo data show that heat-related excess mortality is strongly concentrated among older age groups, especially individuals aged 65 years and over, with Andalusia being one of the regions most affected during episodes of extreme heat. This pattern highlights the sensitivity of elderly populations to thermal stress and their limited capacity to cope with prolonged periods of high temperatures. Income level is a widely recognized determinant of vulnerability to extreme heat, as it directly influences adaptive capacity, access to cooling resources, housing quality, healthcare, and mobility [46–49]. The population grid (250 × 250 m) contains information on the number of individuals aged 65 and over; however, it does not include income data. To incorporate socioeconomic information, average income at the census tract level—the finest available spatial resolution—was used, and these values were subsequently assigned to each grid cell based on their spatial correspondence within the respective census tract, ensuring consistency between demographic and socioeconomic datasets. Given the strong skewness of socioeconomic variables and the fact that extreme values represent real territorial situations rather than data errors, no winsorization was applied. Variables were normalized using observed minimum and maximum values to preserve full variability. The resulting composite vulnerability index was subsequently integrated into the population grid, and vulnerability values were classified into five ordinal classes—very low, low, medium, high, and very high—providing a standardized representation of population vulnerability at the grid-cell level and ensuring methodological consistency with the heat hazard assessment.

3.3. *Accessibility of potential climate shelter network*

The starting point is a systematic review of other national and international networks [50–56]. This review aims to learn about the facilities and criteria used in other climate shelter networks so they can be adapted to the specific context of Andalusia. Following the recommendations of the Barcelona City Council [51], the criteria for the selection of the facilities to be used as climate shelters are as follows: 1) provide refuge from heat without disrupting normal activities; 2) be indoor air-conditioned or shaded outdoor spaces; 3) be free of charge (except municipal pools); and 4) be easily accessible, preferably with free water and seating. According to these criteria adapted to Andalusia thirteen typologies have been identified both indoor equipment (Public libraries, faculties, sport centers, food markets, religious buildings) and outdoor equipment: beaches equipped with facilities such as showers, drinking fountains, water kiosks, or shaded areas with access to potable water that allow visitors to cool down, beaches lacking these facilities but heavily used by the population during heat events, municipal swimming pools, green spaces with drinking water and shadow and green spaces with heavy shadow. The data were obtained from [43,57] and were processed by removing false negatives and incorporating new shelters not identified in the original data sources.

Once the potential climate shelter network was established, a Network Dataset has been generated for the whole of Andalusia using road network data extracted from OSM (Geofabrik). After a topological review of the road network, the data have been processed and structured for use as an analysis network in ArcGIS Pro. Based on the Network Dataset, a spatial coverage analysis was carried out using the "Service Area" tool. Each of the Service Areas was configured to measure the walking response time, at a rate of 4 km/h, from the shelters with isochrones of 5, 10, and 15 min. Isochrones are selected based on the 15-min city concept [58] and Barcelona City Council's 5-min target for 2030 [59], with an intermediate 10-min interval. Climate shelters are used as facilities, differentiated by each of the 13 types of climate shelters identified (as defined). As a result, 13 polygonal layers are obtained, each with 3 polygons resulting from the 3 established isochrones. Once the isochrones have been established, the corresponding score is defined for each of these time thresholds. In this case, the greater the accessibility to shelters, the higher the score (15 min = weight 0.25; 10 min = weight 0.5; 5 min = weight 1).

As discussed by Ref. [50], not all public equipment considered as climate shelters provide the same function and service to the population. Therefore, experts were consulted to determine the importance and quality of each type of climate shelter. Based on the results obtained, different relative weights have been assigned to each type of shelter. To establish the weights, a normalized arithmetic progression was used based on Equation (1).

Equation 1

Table 1
Weighting of the score assigned to the types of climate shelter.

Typology	Weight
Green spaces with drinking water	14.29
Urban Beaches with water and restrooms	13.19
Urban Beaches without water and restrooms	12.09
Green spaces without drinking water	10.99
Shopping centers	9.89
Public swimming pools	8.79
Libraries	7.69
Museums	6.59
Food markets	5.49
Educational centers	4.40
Religious buildings	3.30
Transportation hubs	2.20
Indoor sports centers	1.10

Source: Compiled by the authors

$$x_i = \frac{i}{\sum_{j=1}^{n} J}*100 = \frac{i}{\frac{n(n+1)}{2}}*100$$

Where.

x_i = weight assigned to category i
i = category number (from 1 to 13)
$\sum_{j=1}^{n} J = \frac{n(n+1)}{2}$ = sum of the first natural whole numbers

In our case:

$$\sum_{j=1}^{13} J = \frac{13*14}{2} = 91$$

Table 1 shows the results obtained after applying Equation (1) for each type of climate shelter.

Equation 2

$$x_i = \frac{i}{91}*100$$

The 13 network analyses obtained —one for each type— are unified with their corresponding service areas in a single spatial database. The result of pedestrian accessibility to the network of climate shelters is obtained using Equation 3.

Equation 3.

$Accessibility\ score = Isochrone\ weight*Shelter\ typology\ weight$

To classify the accessibility scores and facilitate their interpretation, a categorical scheme based on the statistical distribution of values was applied. Before classification, the distribution of accessibility scores was examined to identify potential outliers that could distort measures of central tendency. No extreme values requiring exclusion were detected. Summary statistics were then calculated, including the mean and standard deviation, which were used as reference parameters to define class thresholds. Accessibility values were subsequently grouped into five ordinal classes—very low, low, medium, high, and very high—using intervals defined by deviations from the mean. This standard deviation–based classification allows for a balanced differentiation between areas with markedly limited access to climate shelters and those with comparatively high accessibility, while preserving relative contrasts across the regional scale. The use of five classes ensures methodological consistency with the hazard and vulnerability assessments and supports comparability across the different prioritization matrices developed in the study.

3.4. Priority matrix

Based on the integrated data on hazard, vulnerability, and accessibility, priority matrices were generated to identify areas requiring targeted interventions. First, a matrix combining accessibility and hazard was constructed to assess areas where populations are both exposed to high heat risk and have limited access to climate shelters. Second, a matrix crossing accessibility and vulnerability was developed to identify areas where socially vulnerable populations also face limited accessibility. Table 2 presents the combination matrix linking accessibility with hazard and vulnerability, according to the classification scheme applied to each variable.

Finally, a composite matrix integrating hazard, vulnerability, and accessibility was produced, providing a comprehensive spatial prioritization (Table 3). The prioritization matrices are based on ordinal decision rules that combine classes of hazard, vulnerability, and accessibility; no additive or weighted aggregation of indicators is applied.

Table 2
Accessibility–hazard and accessibility–vulnerability combination matrices by class.

		Hazard/Vulnerability				
		Very Low	Low	Medium	High	Very high
Accessibility	**Very high**	Very Low	Very Low	Low	Low	Medium
	High	Very Low	Low	Low	Medium	High
	Medium	Low	Low	Medium	High	High
	Low	Low	Medium	High	High	Very high
	Very low	Medium	High	High	Very high	Very high

Source: compiled by authors

Table 3
Accessibility–hazard–vulnerability combination matrix by class.

		Accessibility & Vulnerability				
		Very Low	Low	Medium	High	Very high
Accessibility & Hazard	**Very Low**	No priority	No priority	No priority	Low	Medium
	Low	No priority	No priority	No priority	Medium	Medium
	Medium	No priority	No priority	Low	Medium	High
	High	Low	Medium	Medium	High	Very high
	Very high	Medium	Medium	High	Very high	Very high

Source: Compiled by the authors

Since the population grid contains total population data, it is possible to quantify the number of people residing in each priority area. By overlaying the priority classification derived from the combined hazard, vulnerability, and accessibility assessment onto the grid, we can estimate the total population affected within each priority class. This approach allows for a direct assessment of population exposure and potential impact, providing actionable information for targeted planning and resource allocation in the design and implementation of climate shelter networks. This methodological framework enables a consistent, population-weighted identification of priority areas, ensuring that heat hazard, social vulnerability, and accessibility to climate shelters are jointly considered in a spatially explicit and operational manner.

4. Results

The results are presented following the analytical sequence of the methodological framework. First, the spatial patterns of the thermal hazard index and the socioeconomic vulnerability index, constructed from climatic and demographic variables, are described. Next, pedestrian accessibility to the potential climate shelter network and its distribution into five classes is characterized. Finally, the prioritization maps derived from the matrices (hazard–accessibility, vulnerability–accessibility, and joint integration) are shown, highlighting both the territorial patterns and the resident population in each priority level.

4.1. Heat hazard and vulnerability assessment

Fig. 2 shows both the heat hazard and the vulnerability Index constructed. The hazard index reveals a clear physical-climatic pattern. The uneven distribution of intervals reflects the concentration of high values inland and the lower variability along the coast. The highest values are concentrated in the interior of Andalusia, particularly in the provinces of Sevilla, Córdoba, and Jaén, as well as in some inland areas of Granada and Málaga. In contrast, the lowest values are in the Atlantic and Mediterranean coastal zones—Cádiz, Huelva, Málaga, Granada, and Almería—where maritime influence moderates' extreme temperatures.

The spatial patterns of the vulnerability index show greater heterogeneity, as they depend on sociodemographic variables. The highest values appear in rural inland areas and in certain urban grids within major cities. The lowest values are concentrated in well-established urban zones with more favorable sociodemographic indicators—such as areas of Málaga, East Sevilla, North Córdoba, and various coastal sectors. The interval configuration reflects a dispersed distribution, with many medium values and notable extreme values, particularly in territories with pronounced aging and lower income levels.

4.2. Accessibility of potential climate shelter network

Table 4 summarizes the total number of shelters by type.

The network has a total of 10,458 points considered as potential access to climate shelters, of which 7561 are outdoors and 2897 are indoors. Among the outdoor access points, it is worth noting the high number of access points to beaches, which account for 72% of outdoor shelters. Among the indoor points, religious buildings (1,674) stand out, accounting for 57% of indoor shelters, and libraries (92), accounting for 3%. These two types are much less functional than other types of shelters, as they are designed for a very specific activity and have more restricted opening hours. A noteworthy fact is the high number of green spaces that do not have drinking water

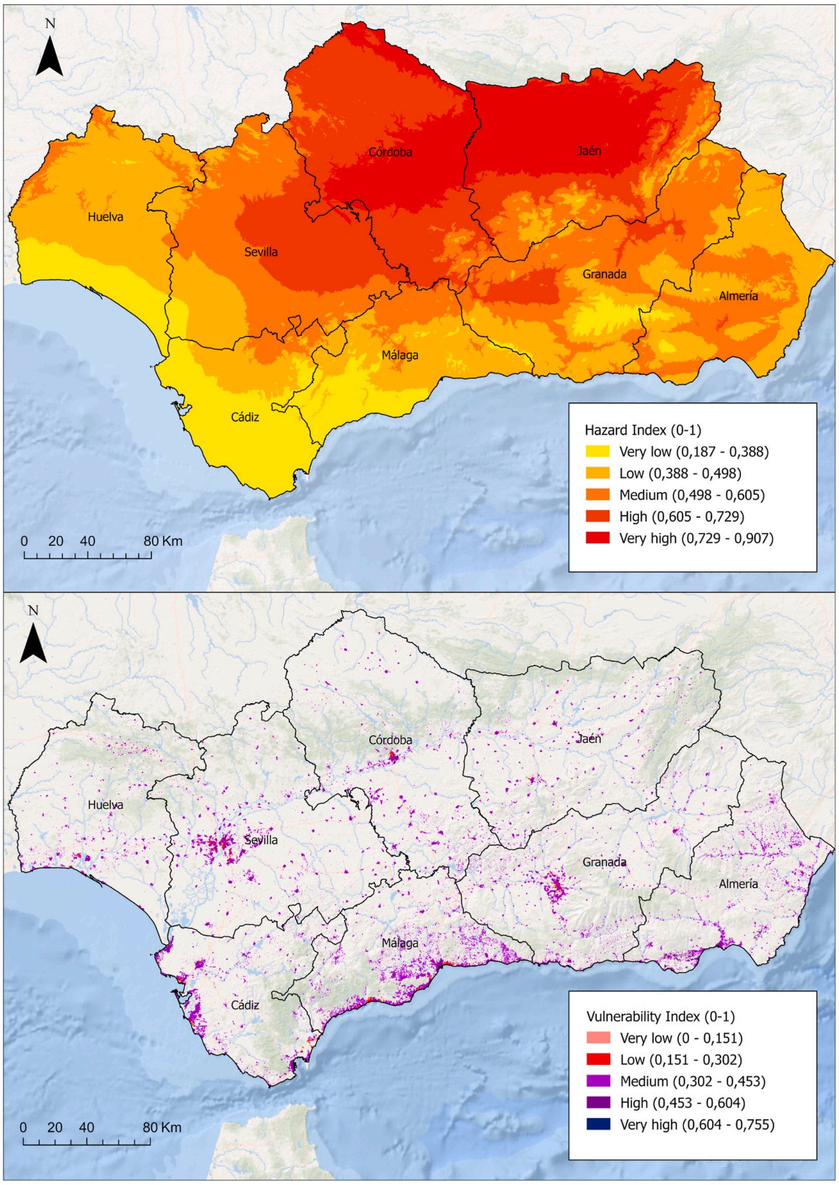

Fig. 2. Hazard Index (above) and Vulnerability Index (below)
Source: compiled by authors from IECA (2024) and INE (2024)

(337), compared to green spaces that do (205). Fig. 3 shows the results of Equation 2 (accessibility score) and the areas distribution of five accessibility classes.

The accessibility map of the climate shelter network across Andalusia reveals a clear urban-coastal versus interior-rural pattern. Most of the interior provinces, including Jaén, Córdoba, Sevilla, Granada, and Almería, exhibit very low to low accessibility, reflecting the sparse distribution of climate shelters. In contrast, coastal areas and metropolitan centers—notably Sevilla, Málaga, Granada, and Cádiz—show medium to high accessibility, where population density and shelter concentration are higher. Detailed views of Córdoba and Málaga illustrate this pattern at the local scale: concentric shapes can be observed around the central areas of urban spaces, which constitute the predominant spatial pattern. In Córdoba, high and very high accessibility is concentrated in the urban core, with peri-urban and rural areas showing medium to very low accessibility; in Málaga, high accessibility is concentrated along the coast and urban areas, while interior and mountainous zones have lower access. These results highlight that urban and coastal populations benefit most from the potential climate shelter network, whereas interior and rural areas remain under-served, indicating a need to expand coverage and improve equity in heat risk protection.

Table 4
Number of climate shelters by type.

Climate shelter typology	Number of climate shelters
Indoor climate shelters	
Libraries	92
Educational centers	51
Sports centers	281
Public markets	246
Museums	171
Transportation hubs	136
Shopping centers/Malls	246
Religious buildings	1674
Outdoor climate shelters	
Public swimming pools	430
Urban Beaches with water and restrooms	755 (access)
Urban Beaches without water and restrooms	5834 (access)
Green spaces with drinking water	205
Green spaces without drinking water	337

Source: Compiled by the authors

4.3. Priority areas based on accessibility and heat hazard

Fig. 4 analyses the spatial distribution of priority areas for intervention against extreme heat in Andalusia (southern Spain), based on a composite prioritization matrix that integrates five levels of heat hazard and five levels of accessibility to a potential network of climate shelters. The resulting index is represented on a population grid of 250 × 250 m, allowing for a fine-grained assessment of population exposure and territorial inequalities.

At the regional scale, the results reveal a highly uneven spatial distribution of priority levels, with a clear concentration of high and very high priority areas along the Mediterranean coastline and within major urban agglomerations in the interior of the region. These patterns reflect the combined effect of elevated thermal Hazard and limited accessibility to climate shelters. The Mediterranean coastal corridor, particularly along the provinces of Málaga, Granada, and Almería, shows a near-continuous band of grid cells classified as high or very high priority. This spatial continuity suggests a persistent heat exposure, urban compactness, and intense land artificialization, which together exacerbate thermal stress and constrain the availability of nearby shelter. In these areas, the prioritization index highlights not isolated hotspots but extensive urbanized zones where large segments of the population are simultaneously exposed and insufficiently protected.

In contrast, inland urban areas such as the metropolitan regions of Sevilla, Córdoba, and Granada present concentrated clusters of high-priority cells, embedded within a more heterogeneous surrounding matrix. These clusters are indicative of strong intra-urban contrasts, where neighborhood-level differences in urban morphology, green infrastructure, and proximity to potential shelters play a decisive role in shaping heat risk. The results underline that, even within the same city, exposure and adaptive capacity are unevenly distributed.

Most rural and sparsely populated areas of Andalusia display low to medium priority levels, reflecting lower population exposure and, in some cases, more favorable microclimatic conditions or proximity to natural shading and open spaces. However, the presence of isolated high-priority grid cells within these territories indicates that vulnerability is not exclusively an urban phenomenon. Small compact settlements, ageing populations, or limited-service provision can generate localized pockets of elevated risk that may be overlooked in analyses based on coarser spatial units.

The two local case studies included in the lower panels of the figure provide additional insight into the spatial logic of the prioritization index. In the case of Sevilla, the map reveals a highly fragmented pattern of priority levels within the urban fabric. High and very high priority cells are interspersed with areas of lower priority, highlighting sharp neighborhood-level disparities in accessibility to climate shelters. This fragmentation underscores the importance of micro-scale interventions and proximity-based planning, as small variations in distance or urban form can significantly affect heat risk outcomes. Conversely, the coastal area of Málaga exhibits a more continuous spatial pattern of elevated priority, with extensive zones classified as high or very high priority along the urbanized coastline. Here, the challenge is less related to identifying isolated vulnerable neighborhoods and more to addressing the cumulative pressure of heat exposure affecting large, densely populated areas with limited redundancy in shelter provision.

The population-based analysis reveals a pronounced concentration of inhabitants in areas requiring urgent intervention. Of Andalusia's total population (8,354,330 inhabitants), 816,000 people (9.7%) reside in very high-priority areas, while 4.25 million (50.0%) live in high-priority areas. Altogether, nearly 60% of the population is exposed to conditions characterized by high heat hazard and limited accessibility to climate shelters. A further 1.77 million inhabitants (21.9%) are in medium-priority areas, indicating intermediate levels of risk. In contrast, low- and very low-priority areas account for a considerably smaller share of the population, with 1.27 million (15.2%) and 243,000 people (2.9%), respectively. These results confirm that heat-related risk in Andalusia is widespread and predominantly concentrated in highly prioritized areas, reinforcing the need for population-focused and spatially targeted disaster risk reduction strategies.

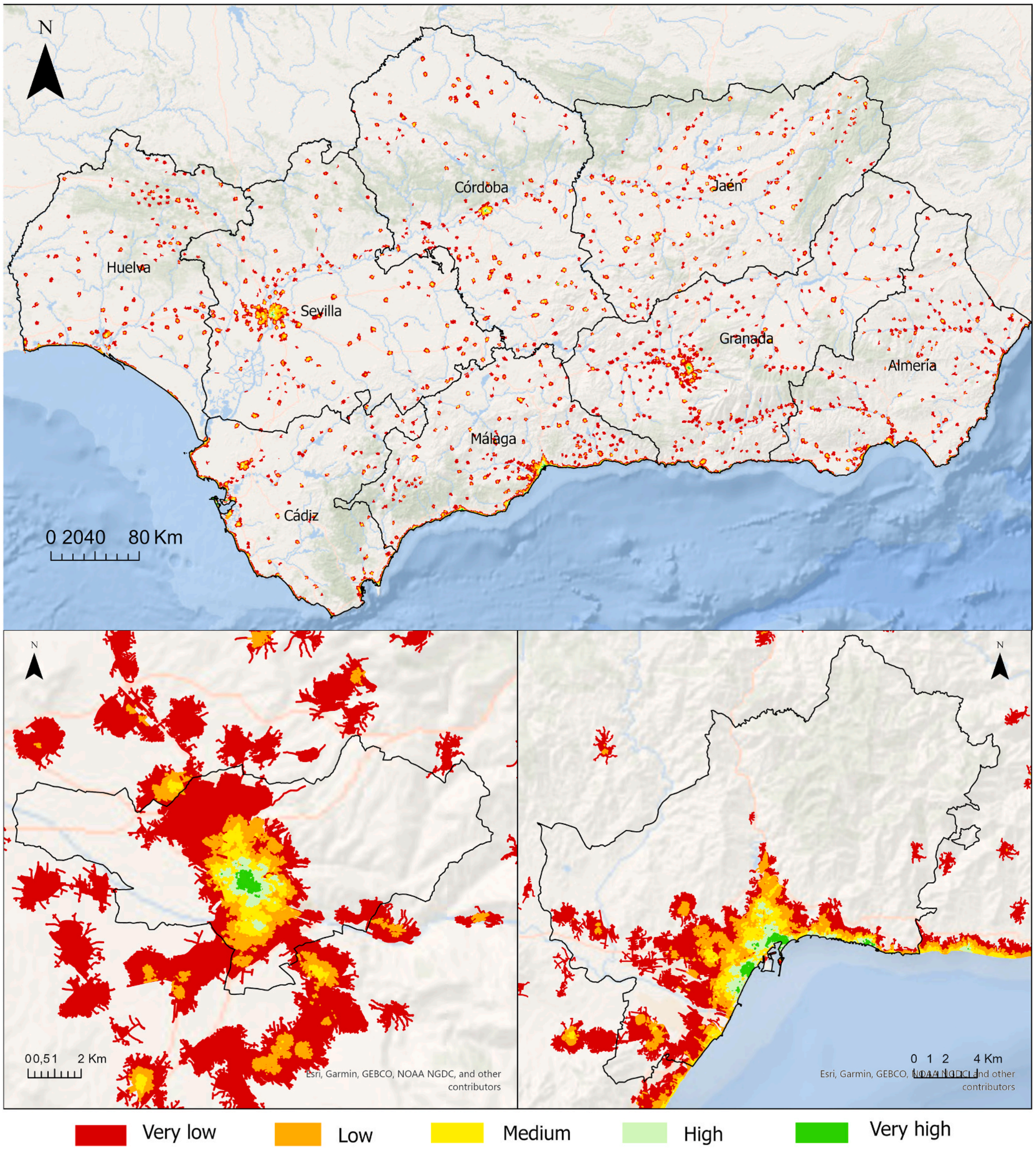

Fig. 3. Accessibility areas based on five classes in Andalucía and detailed cases of Córdoba (left) and Málaga (right) municipalities.
Source: author's own

4.4. Priority areas based on accessibility and vulnerability

Fig. 5 analyses the spatial distribution of priority areas for intervention against extreme heat in Andalusia (southern Spain), based on a composite prioritization matrix that integrates five levels of vulnerability and five levels of accessibility to the potential network of climate shelters.

Prioritization reveals a spatial pattern that is both more territorially extensive and socially pervasive than that observed in the hazard-based prioritization. While the previous map concentrated high-priority areas along the Mediterranean coast and major urban agglomerations, this vulnerability–accessibility framework identifies high-priority conditions across much of the Andalusian territory, including medium-sized cities, peri-urban areas, and rural settlements.

At the regional scale, high-priority grid cells dominate the map, forming a dense mosaic rather than isolated clusters. Urban areas such as Granada, Jaén, and Sevilla exhibit clear concentrations of high and very high priority cells, although with distinct spatial configurations: more compact and continuous in Granada, and more fragmented in Jaén. In contrast to the hazard-based map, coastal areas lose relative prominence, while inland and rural territories gain importance, reflecting the spatial distribution of ageing populations and lower income levels combined with uneven accessibility to climate shelters. This spatial pattern is strongly supported by

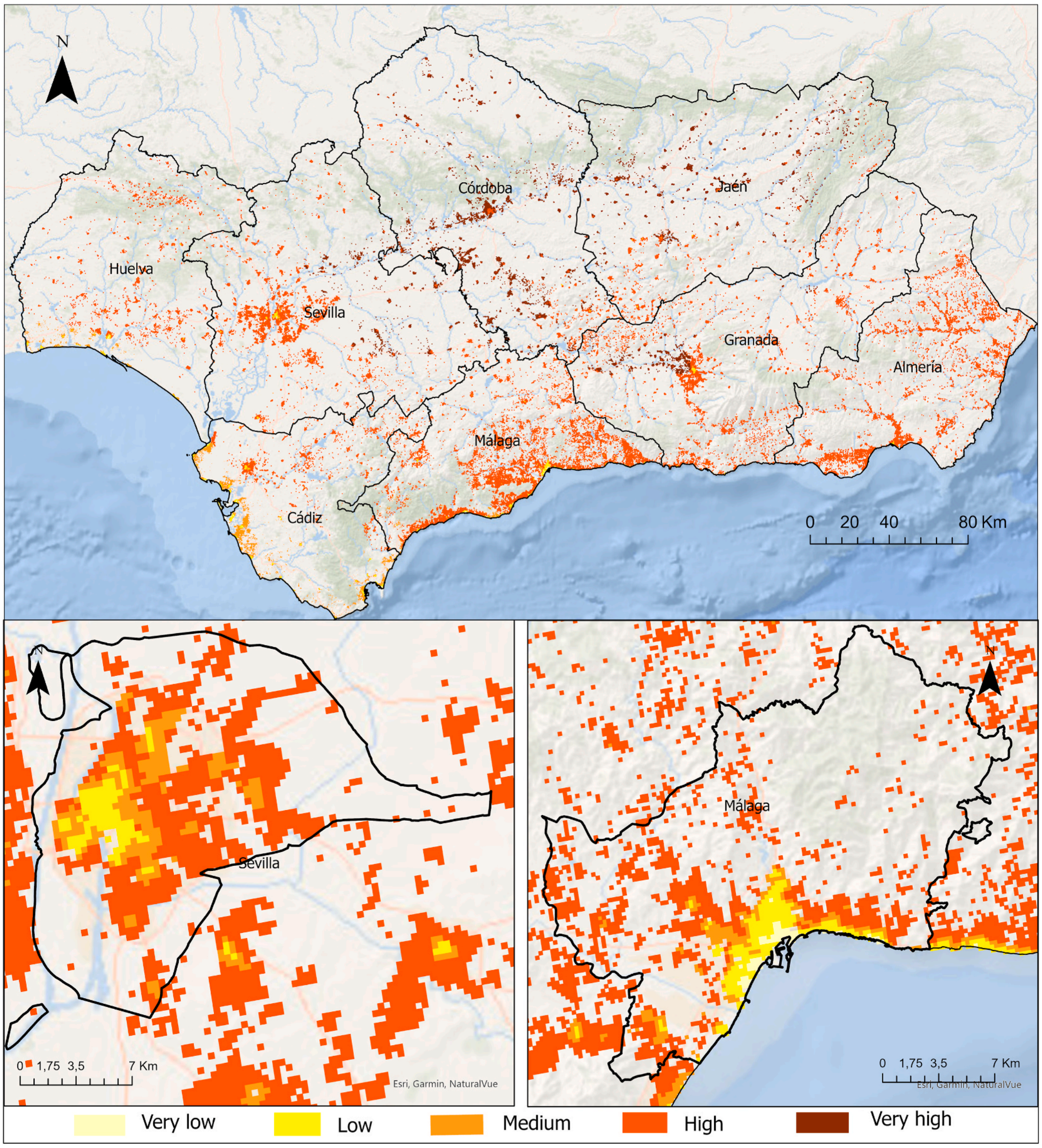

Fig. 4. Priority areas based on accessibility and heat hazard in Andalucía and detailed cases of Sevilla (left) and Málaga (right) municipalities. Source: author's own

the population data. Of the total Andalusian population, 249,845 inhabitants (3.0%) reside in very high-priority areas, and 6.16 million (73.7%) in high-priority areas, meaning that over three quarters of the population are exposed to conditions of elevated social vulnerability and limited accessibility. Medium-priority areas account for 1.26 million inhabitants (15.0%), while low and very low-priority areas together represent less than 9% of the population. Compared with hazard-based prioritization, the share of population in high-priority categories increases substantially, indicating that social vulnerability broadens and intensifies the geography of risk.

4.5. Priority areas based on heat hazard, vulnerability and accessibility

The final prioritization map integrates heat hazard, socioeconomic vulnerability, and pedestrian accessibility to climate shelters, resulting in five classes of priority for intervention: no priority, low, medium, high, and very high. This classification provides a spatially explicit synthesis of compounded heat risk and adaptive capacity across Andalusia, highlighting both large-scale territorial gradients and fine-grained intra-urban disparities (Fig. 6)

Unlike the individual hazard–accessibility and vulnerability–accessibility maps, this integrated framework identifies areas where limited accessibility fails to compensate for the combined effects of thermal exposure and social vulnerability, providing an operational representation of priority for climate shelter planning. Areas classified as no priority correspond to grid cells where, according to the

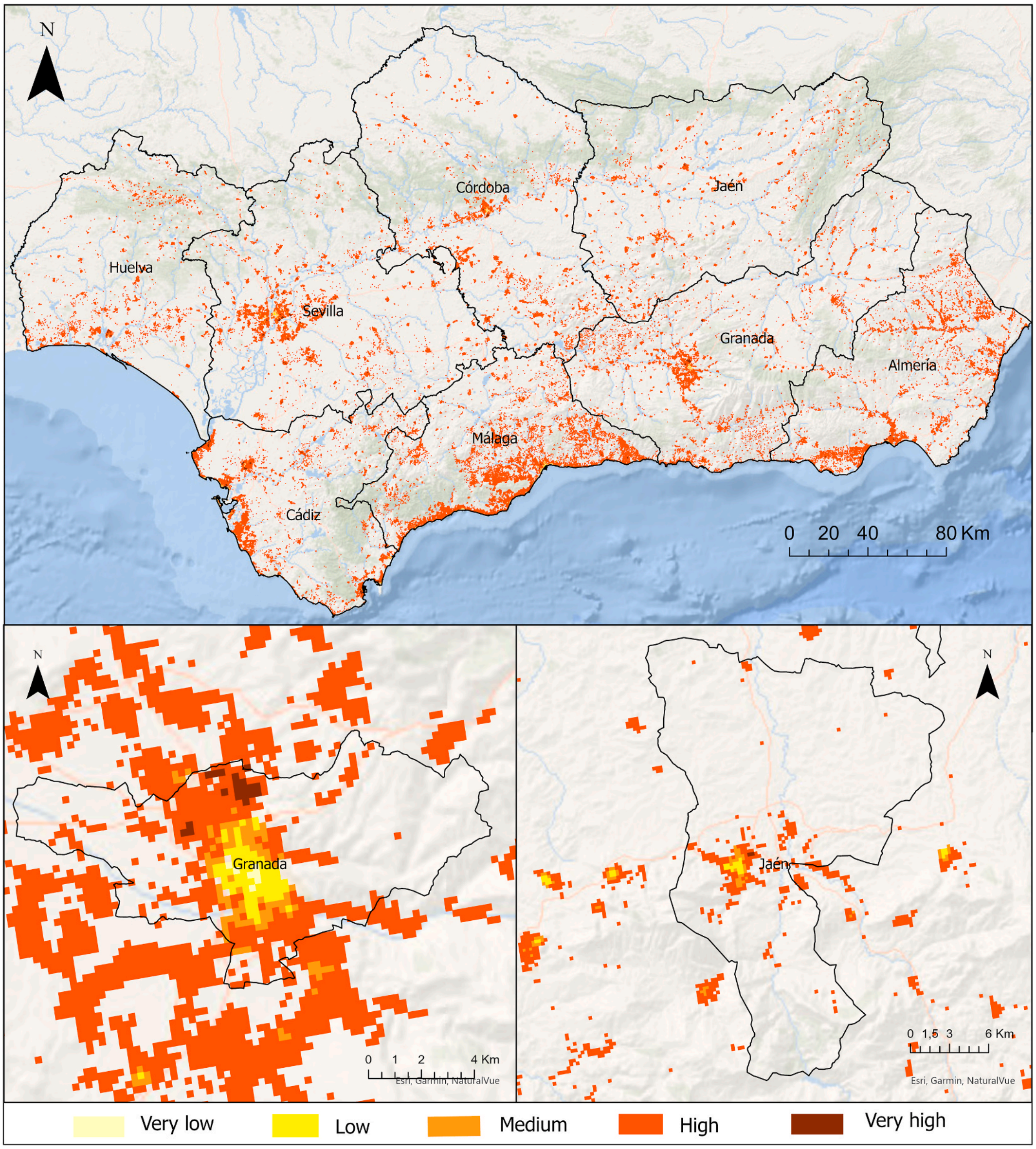

Fig. 5. Priority areas based on accessibility and vulnerability in Andalucía and detailed cases of Granada (left) and Jaén (right) municipalities. Source: authors' own elaboration

ordinal decision rules of the prioritization matrix, accessibility conditions are sufficient to offset existing levels of heat hazard and population vulnerability. These areas are spatially limited and appear primarily as compact clusters within well-served urban cores, particularly evident in the detailed cases of Seville and Granada. Their presence reflects zones with dense and diversified networks of potential climate shelters and short pedestrian access times, rather than the absence of heat exposure or vulnerable populations. Consequently, no-priority areas should be interpreted as territories where current shelter provision is relatively adequate, requiring mainly maintenance, optimization, and operational improvements rather than network expansion. Low-priority areas form narrow transitional belts surrounding no-priority zones or appear as scattered patches within consolidated urban areas. These areas typically combine moderate hazard or vulnerability levels with reasonably good, though not optimal, accessibility to climate shelters. In territorial terms, they represent zones of emerging imbalance, where small declines in accessibility or future increases in hazard could rapidly elevate priority levels. From a planning perspective, these areas are suitable for preventive actions aimed at reinforcing existing shelters, improving pedestrian connectivity, and increasing functional redundancy within the network. Areas classified as medium priority are widely distributed across Andalusia and constitute an important intermediate category. They often correspond to consolidated urban neighborhoods and peri-urban areas where hazard and vulnerability begin to overlap, but where accessibility still provides partial mitigation. In the regional context, medium-priority areas are particularly visible in the Atlantic coastal provinces and

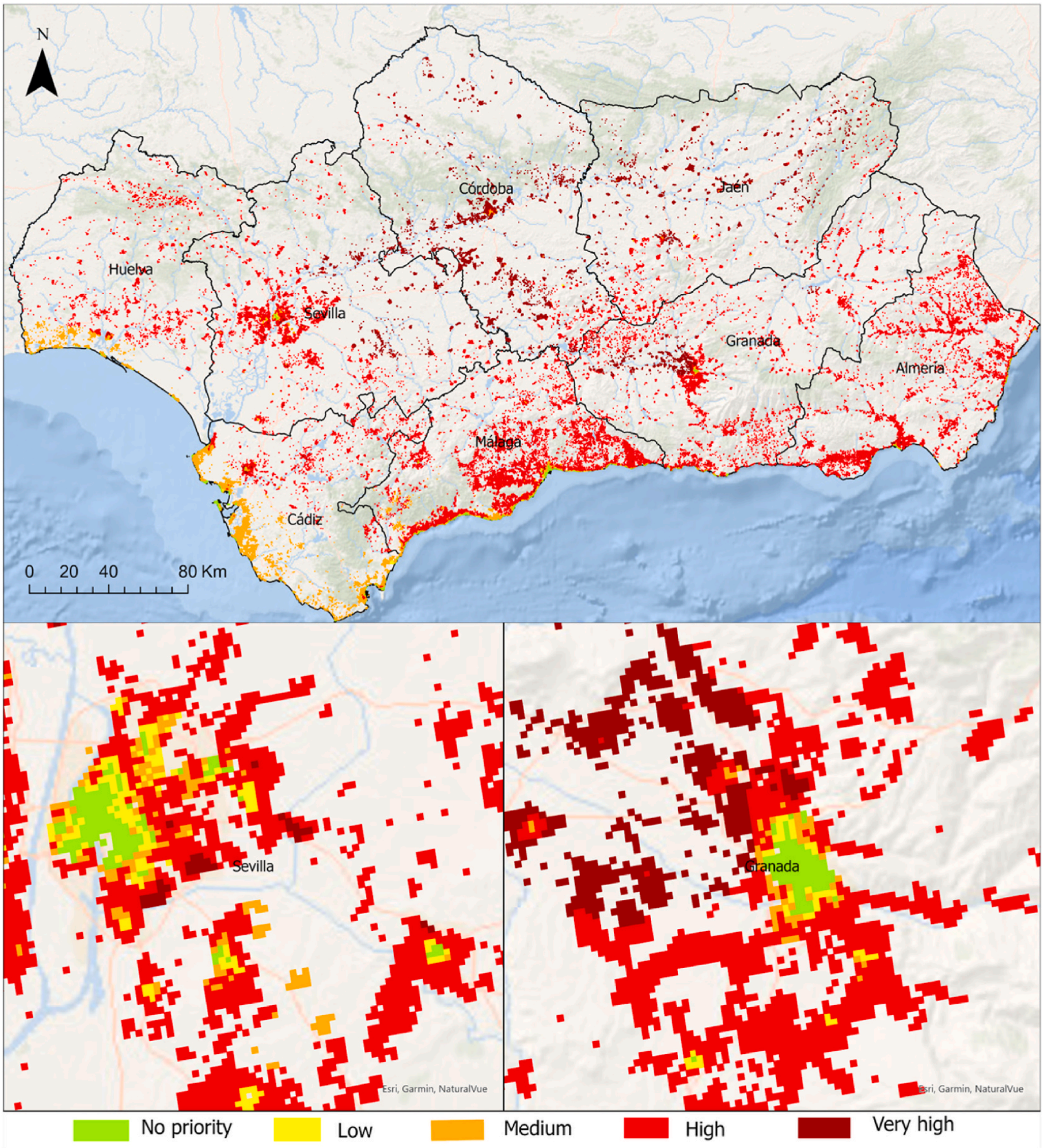

Fig. 6. Final Priority areas based on accessibility, heat hazard and vulnerability in Andalucía and detailed cases of Sevilla (left) and Granada (right) municipalities.
Source: authors' own elaboration

in intermediate urban systems, reflecting contexts where thermal hazard is moderate but social vulnerability and uneven accessibility increase sensitivity to heat. These areas represent strategic targets for anticipatory adaptation, as targeted improvements in accessibility or shelter quality could prevent their transition into higher priority classes.

High-priority areas dominate the final prioritization map and reveal the structural geography of insufficient protection against extreme heat. They are concentrated in dense urban environments, metropolitan peripheries, and major urban corridors, including the Guadalquivir axis and large coastal agglomerations. These areas emerge where elevated heat hazard and/or social vulnerability coincide with accessibility levels that are inadequate to ensure effective protection. In the detailed urban cases, high-priority cells form extensive and often contiguous zones surrounding better-served cores, highlighting strong intra-urban inequalities in access to climate shelters. Their spatial extent indicates that, for a substantial share of the population, existing shelter networks do not provide sufficient coverage under current climatic and demographic conditions. The very high priority class identifies the most critical territories, where high or very high hazard and vulnerability converge with very low accessibility to climate shelters. These areas appear as concentrated clusters rather than diffuse patterns, frequently located in peripheral urban neighborhoods, compact settlements, or disadvantaged urban sectors. In cities such as Sevilla and Granada, very-high-priority zones are embedded within the urban fabric but remain clearly segregated from well-served central areas, underscoring sharp spatial inequalities in adaptive capacity. These locations represent immediate intervention hotspots, where deficiencies in shelter availability and pedestrian access are most likely to translate into adverse health outcomes during extreme heat events.

The integrated prioritization highlights that heat-related risk in Andalusia is not solely a function of climatic exposure or social vulnerability but is critically shaped by the spatial configuration and effectiveness of climate shelter networks. The resulting pattern emphasizes urban and intra-urban disparities, rather than a simple coastal–interior divide. While rural areas generally show lower priority levels, the presence of isolated high and very-high-priority cells demonstrates that local conditions can generate significant risk even outside major cities.

The data indicate that a large share of Andalusia's resident population is concentrated in high or very high priority intervention areas. Almost half of the population (45.88%, 3,832,853 people) lives in high-priority areas, while a further 11.55% (965,056 people) reside in very high-priority areas. An additional 23.14% (1,933,192 people) live in areas of medium priority. In contrast, significantly smaller proportions of the population live in low-priority (5.44%, 454,731 people) and no-priority areas (13.99%, 1,168,498 people). More than 80% of the Andalusian population is exposed to some level of priority related to hazard, vulnerability, and limited access to climate shelters, highlighting the urgent need for targeted climate adaptation and risk reduction policies in the region.

5. Discussion

This study advances current approaches to heat-related disaster risk reduction by explicitly integrating heat hazards, social vulnerability and accessibility to climate shelter networks within a unified, spatially explicit framework. It demonstrates that the relevant analytical unit for risk reduction is the territorial mismatch between where the risk is concentrated and where the protection offered by climate shelters is accessible. In a Mediterranean context identified as a climate hotspot, where thermal extremes and their impacts are intensifying, this integration provides a holistic diagnosis of risk aligned with recent international policy frameworks that emphasize the need for equity-oriented and preparedness-focused adaptation strategies [1,2].

A central contribution of the study lies in identifying territorial mismatches between heat risk and access to climate shelters. The results demonstrate that the nominal availability of potential shelters does not guarantee effective protection during extreme heat events. Areas with a high density of facilities may still exhibit limited functional accessibility when pedestrian reachability, spatial configuration, and population distribution are considered. This finding is consistent with prior research demonstrating that, despite their presence within the urban fabric, cooling centers frequently fail to adequately serve heat-vulnerable populations due to accessibility constraints [20,60,61]. By adopting a network-based accessibility approach, the study further reinforces the relevance of proximity and walkability as key determinants of adaptive capacity, echoing broader debates on equity in access to essential urban services.

The study also contributes to debates on maladaptation and path dependency in urban heat adaptation. It identifies a strong relationship between accessibility to climate shelters and the configuration of the settlement system in Andalusia. Provinces with denser, more centralized urban structures centered around medium-sized cities have a more favorable distribution of these spaces, while those with dispersed urban planning or peripheral expansion show greater deficits. Despite the methodological differences with the work of [62], a similar pattern was found: higher accessibility is observed in urban areas, while lower accessibility occurs in peripheral and rural environments. From a climate justice perspective, the results demonstrate that a shelter network based solely on "what already exists" may generate uneven protection; therefore the results caution against adaptation strategies that inadvertently amplify spatial and social inequalities. The evidence of large population pockets in high-priority categories suggests that shelter-based adaptation can become a mechanism for amplifying inequalities if it is not governed by explicit equity criteria (e.g., prioritizing vulnerability and accessibility over real estate opportunity or urban centrality). Similar concerns have been raised in relation to other cooling interventions, such as green infrastructure, which—if not carefully governed—can interact with processes of socio-spatial exclusion and climate gentrification [25]. In this sense, the framework proposed here provides a diagnostic tool to anticipate such risks and guide more just and preventive adaptation pathways.

Andalusia is a particularly relevant case study because it combines high hazard, exposure and territorial heterogeneity (metropolis, dense coastline, aging rural interior). The pattern observed in Andalusia suggests that heat risk operates as a compound risk: it is not enough to consider hazard alone or socioeconomic vulnerability alone; rather, criticality arises when both overlap with deficits in accessibility. This interpretation is consistent with recent frameworks that emphasize that inequality in the face of heat is multidimensional, dynamic, and intersectional, and that planning should focus on those who are systematically excluded from adaptation measures [60]. A joint reading of the three maps (hazard–accessibility, vulnerability–accessibility, and integrated) suggests that the geography of heat risk in Andalusia does not respond to a single gradient (coast/interior or urban/rural), but rather to different configurations depending on the dominant mechanism: thermal hazard tends to be organized by regional physical and climatic conditions, while social vulnerability introduces discontinuities associated with aging and income, and accessibility rearranges the pattern according to urban structure, centrality, and pedestrian connectivity.

The work presented here is conceived as a practical guide for the planning and implementation of climate shelter networks. In particular, the proposed potential network of climate shelters—based on established shelter typologies and operational criteria from existing experiences—should not be understood as a fixed blueprint, but rather as a flexible reference framework that can guide adaptation to local contexts. By identifying strategic areas, priority actions, and spatial criteria in advance, this approach supports the early integration of heat adaptation measures into territorial planning and disaster risk reduction processes. In doing so, it promotes a proactive perspective that anticipates climate stress scenarios and reduces dependence on reactive responses to extreme events. This is especially relevant in Spain, where climate shelter networks remain at an incipient stage [40], despite being recognized as a priority in national and municipal urban heat adaptation strategies [63].

A key contribution of the study is that it translates the integrated assessment into an operational prioritization logic that is compatible with urban planning and civil protection protocols: it identifies where it is most effective to (i) expand the network, (ii) improve conditions of use (schedules, opening during peaks hours), (iii) enable temporary solutions, and (iv) strengthen communication and assisted transportation. In this sense, the approach is aligned with the evolution of urban policies that establish specific targets for pedestrian proximity to shelters.

This study has several limitations that should be considered when interpreting the results. First, accessibility is modeled as standard walkability (constant speed), without explicitly incorporating friction due to slope, shade, sidewalk quality, or thermal conditions along the route, all factors that could reduce actual mobility in extreme episodes. Second, as it is based on potential facilities, effective functionality depends on variables that are not always available in a consistent manner (opening hours, actual air conditioning, capacity, opening protocols in case of alerts). The effectiveness of a climate shelter will depend on its accessibility, territorial distribution, and suitability to local needs. The literature on cooling centers shows that, even with reasonable locations, effectiveness depends on operational governance (emotional accessibility, schedules, and outreach on critical days) and on implementation focused on vulnerable populations, not just the general population [19,40]. In this sense, the authors argue that climate shelter networks should not only be established based on technical criteria, but that their usefulness and usability will depend on their acceptance by the local population. In this regard, the collaborative construction of these networks through mechanisms of public participation and/or citizen science should be considered when establishing these networks. Third, the vulnerability index uses robust proxies (age and income), but does not include other relevant dimensions (health, social isolation, energy poverty, or housing), which may underestimate vulnerability in some settings. Although other studies have included a broader set of socioeconomic indicators, these variables are not justified in the Andalusian context for assessing heat-specific vulnerability. Significant numbers of Northern and Central European residents migrate for lifestyle and climate reasons [64,65], typically with higher incomes and better housing. Using the foreign-born population as a vulnerability proxy risks conflating affluent migrants with more vulnerable groups, overestimating risk in wealthy areas, and obscuring vulnerability in lower-income neighborhoods. Likewise, the MoMo (Daily Mortality Monitoring System) reports on heat-related mortality in Andalusia do not provide consistent evidence of significant differences by sex. In the absence of robust and context-specific empirical support, sex was therefore not included as a vulnerability variable in this analysis. Age and income, by contrast, show a more direct and consistent association with exposure, sensitivity, and adaptive capacity to extreme heat. In addition, the use of the population grid enables a higher spatial resolution and improves the robustness of accessibility analyses compared to aggregated administrative units [20]. However, this spatial detail also entails significant data constraints, particularly regarding health variables, which are protected by statistical confidentiality and are only available at supra-municipal scales, thus limiting their integration at the grid level.

Future research could improve the robustness of the framework by integrating (i) thermally informed accessibility (shaded routes, sun exposure, heat-aware routing), (ii) shelter capacity and reliability (capacity, air conditioning, opening during heat episodes), (iii) assisted mobility and public transportation for people with limitations, and (iv) validation with actual usage data during alerts (counts, telephony, surveys, municipal data). In addition, it would be valuable to evaluate the framework under alternative climate and demographic scenarios to estimate future gaps and guide preventive investments, in line with work that combines thermal risk and socioeconomic trajectories [66].

Overall, the study shows that planning for climate shelters requires a shift from an inventory-based approach ("what facilities exist") to a risk reduction approach ("who can get there, when and under what conditions, in places where risk is concentrated"). The key contribution is therefore the spatially explicit identification of mismatches between hazard, vulnerability, and accessibility, which allows for the prioritization of interventions with a focus on equity and direct practical utility for urban adaptation and civil protection under a scenario of intensifying extreme heat in the Mediterranean.

6. Conclusions

This study develops and applies an integrated, spatially explicit framework to identify priority areas for heat-related disaster risk reduction through climate shelter planning. By jointly considering heat hazard, population vulnerability, and pedestrian accessibility, the approach moves beyond inventory-based assessments of cooling infrastructure to provide a risk-informed diagnosis of where climate shelters are most urgently needed and for whom.

Applied to Andalusia, a Mediterranean climate change hotspot, the results reveal significant territorial mismatches between areas of high heat exposure, socially vulnerable populations, and access to potential climate shelters. While coastal and metropolitan areas have high thermal hazard, inland cities and peri-urban zones emerge as critical hotspots when vulnerability and accessibility are jointly considered. The integrated prioritization highlights that heat risk is not driven by a single spatial gradient (urban–rural or coastal–inland), but rather by the convergence of climatic, social, and infrastructural factors at fine spatial scales. The findings demonstrate that the nominal availability of shelters does not guarantee effective protection during extreme heat events. Accessibility constraints, urban structure, and the uneven distribution of vulnerable populations play a decisive role in shaping actual response capacity. From a disaster risk reduction perspective, these findings underscores the need to shift from reactive or opportunity-driven deployment of cooling spaces toward proactive, equity-oriented planning strategies explicitly guided by risk and accessibility criteria. Methodologically, the framework is transferable and compatible with the data and institutional capacities of regional and municipal authorities. It offers an operational tool to support targeted interventions, including expanding shelter networks, adjusting opening hours, providing temporary facilities during heat alerts, and implementing complementary measures such as assisted mobility and communication strategies. By aligning spatial prioritization with population exposure, the approach directly supports evidence-based decision-making in climate adaptation and civil protection. Future research should further refine accessibility modeling by incorporating thermal conditions along routes, shelter capacity, quality, and reliability, and by conducting empirical validation using usage data during heat events. Finally, the framework supports a shift from mapping facilities to planning protection: it identifies where shelters should be strengthened or deployed first, based on who is exposed, who is vulnerable, and who can realistically reach cooling resources under extreme heat.

CRediT authorship contribution statement

Jesús Vargas Molina: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Juan Francisco Sortino Barrionuevo:** Writing – review & editing, Formal analysis, Data curation. **Hugo Castro Noblejas:** Writing – review & editing, Methodology, Conceptualization.

Disclosure statement

The authors report there are no competing interests to declare.

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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

Data will be made available on request.

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