Trigger or driver? Tracing the role of climate variability since the Little Ice Age in the abandonment of mountain villages in the Eastern Pyrenees: evidence from historical documents

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Short title: Trigger or Driver? Climate Variability and Village Abandonment since the LIA in the Eastern Pyrenees

Abstract

In recent decades, rural depopulation has emerged as a widespread phenomenon across much of Europe, driven by shared underlying processes but shaped by region-specific dynamics. Understanding how climate variability interacts with socioeconomic dynamics to drive long-term settlement abandonment is critical in the context of current global change. High-mountain regions are particularly sensitive to environmental and social pressures, yet long-term empirical evidence remains limited.

This study analyzes 307 abandoned or uninhabited villages out of 1,214 documented settlements in the Eastern Pyrenees (Catalan and Aranese sector) between 1275 and 2024, based on systematic examination of historical records. Abandonment drivers were classified into natural hazards (geological, climatic, and biological), anthropogenic factors (socioeconomic and geopolitical/historical), and unknown causes, allowing a long-term assessment of climate–society interactions across the Little Ice Age (LIA) and the Industrial Era (IE).

Anthropogenic factors dominate overall, accounting for 78.2% of abandonment cases, whereas natural hazards represent 12.7%. Although natural hazards played a relatively greater role during the LIA, abandonment peaked during the IE, driven primarily by socioeconomic transformations such as rural exodus, declining accessibility, and economic restructuring.

Climate rarely acted as a direct driver but contributed to approximately 15% of cases, often interacting with other stressors. Periods of increased abandonment frequently followed phases of climatic deterioration, suggesting a lagged and indirect influence. These results indicate that climate variability functioned mainly as a vulnerability multiplier rather than as an independent cause of settlement decline.

Overall, the present findings challenge deterministic interpretations linking climate directly to depopulation. Instead, they highlight that settlement persistence depended primarily on adaptive capacity and socioeconomic context. This long-term perspective provides a transferable framework for understanding how climate–society interactions shape settlement dynamics and

emphasizes that the risk under contemporary climate change also lies in its interaction with existing socioeconomic vulnerabilities.

Introduction

In recent decades, rural depopulation has emerged as a widespread phenomenon across much of Europe, driven by common underlying processes but expressed through region-specific dynamics [1–3]. This trend has profoundly transformed rural landscapes, contributing to the emergence of phenomena such as settlement abandonment, land-use change, and demographic ageing in marginal territories [4,5].

At the same time, a growing body of research has emphasized the sensitivity of past societies to environmental and climatic variability, often highlighting cases in which climatic deterioration contributed to social crises, reorganization, settlement relocation, or, in some instances societal collapse [6–10]. In contrast, other studies have demonstrated a remarkable capacity for adaptation, documenting sustained human occupation even under the harsh environmental conditions of the Last Glacial Maximum and other climatic extremes [11].

However, these interpretations often derive from specific regional or temporal contexts, highlighting the need for broader comparative approaches capable of capturing the complexity and variability of long-term human–environment interactions across diverse geographical settings.

High-mountain regions represent a particularly relevant context for investigating these dynamics. Mountain regions cover approximately 36% of the European land surface and are home to around 16% of its population, while also encompassing a remarkable diversity of ecosystems, land-use systems, and socioecological contexts. Consequently, they provide an exceptional setting for exploring the interplay between environmental change, demographic dynamics, and long-term human adaptation [4].

These environments are often characterized by environmental constraints, geographical isolation, limited accessibility, and exposure to natural hazards, but also by long histories of human adaptation. Despite this, long-term empirical information on settlement dynamics in specific mountain regions such as the Pyrenees remains limited or fragmented, with few studies integrating historical, environmental, and socioeconomic perspectives.

This limitation is partly due to the scarcity of high-resolution climatic data in mountain regions such as the Pyrenees. Instrumental records are often incomplete or only extend back to the mid-twentieth century, while historical documentary sources, despite their recognized potential, remain underexplored. Most of these areas were frequently located at strategic positions, such as passages and border zones, which was especially true from the mid-17th century onward. Indeed, the consolidation of European nation-states brought the implementation of the concept of political borders. On the other hand, a variety of events throughout history (such as fires, wars, etc.) led to the total or partial destruction of numerous documents, dramatically reducing the available written record on the effects of many of such events on the smallest populations. As a consequence, the history of certain events is often preserved uniquely through oral accounts passed down from generation to generation.

At the same time, mountain systems do not respond uniformly to global warming, displaying strong spatial variability in climate sensitivity and vulnerability [12–15]. Yet, these landscapes are also characterized by a rapid and visible response to environmental change, as illustrated by the marked retreat of Pyrenean glaciers over recent decades [16].

The Catalan and Aranese Pyrenees, located in the eastern sector of the Pyrenees, offer a valuable case study to address these questions. This region experienced marked climatic variability during the LIA, with temperatures up to ~1°C lower than present and an increased frequency of extreme events [17,18]. Yet, many settlements persisted for centuries under these conditions, while others were abandoned more recently, particularly during the IE. This contrast raises a key question: to what extent has climate acted as a driver of village abandonment, and how has its role varied in relation to socioeconomic transformations over time?

Addressing this question is particularly relevant in the context of contemporary climate change. Current warming trends are occurring at an unprecedented rate and are already generating significant environmental and socioeconomic impacts, with the potential to trigger cascading, system-wide disruptions across both natural and human systems [19,20]. However, public and scientific interpretations of climate–society relationships are sometimes influenced by simplified or misleading narratives about past climate conditions, particularly in high-mountain regions [21]. More importantly, the main risks associated with climate change may not arise from climatic variability alone, but from its interaction with existing socioeconomic vulnerabilities, especially in already fragile mountain regions. In this context, understanding how past climate dynamics influenced human settlement systems provides a critical basis for interpreting present and future climate-related risks.

This study investigates the disappearance, abandonment, and depopulation of villages in the Eastern Pyrenees (Catalan and Aranese sector) over the period 1275–2024. Based on systematic analysis of historical sources, abandonment drivers are classified into natural hazards (geological, climatic, and biological), anthropogenic factors (socioeconomic and geopolitical/historical), and unknown causes. By combining a long-term temporal perspective with a spatially explicit approach, this study aims to (i) quantify the magnitude and patterns of village abandonment, (ii) assess the relative importance of climatic and socioeconomic drivers over time, and (iii) evaluate the role of climate as a potential trigger, driver, or vulnerability multiplier in settlement decline.

Materials and methods

Study area and sources of information

The Pyrenees are a mountain range extending nearly 500 km from east to west, separating between southern France and from the Iberian Peninsula. This study focuses on the southern and northern slopes of the Catalan and Aranese Pyrenees, which constitute the eastern half of the Pyrenees (Fig 1).

Fig 1. Maps showing all documented abandoned villages during the study period (1275–2024). Colours represent the different periods considered (LIA: Little Ice Age; IE: Industrial Era) in the upper map, and the typologies of abandonment causes developed for this study in the lower map. Counties (*comarques*, Catalan administrative subdivisions) are also indicated.

The information collected has, on some occasions, been analysed by subdividing the study area into three regions: the Western, Central, and Eastern Catalan Pyrenees. This territory corresponds to the 11 counties (*comarques*, administrative Catalan subdivisions), included in this study: El *Val d'Aran, L'Alta Ribagorça, El Pallars Sobirà, El Pallars Jussà, L'Alt Urgell, La Cerdanya, El Ripollès, La Noguera, El Berguedà, La Garrotxa,* and *L'Alt Empordà*. Some counties were only partially covered, as the Pyrenees encompass only a portion of their territory. A detailed description of the study area's territorial coverage, including all counties and municipalities considered, is provided in the Supporting Information (S1 Appendix). The S2 Appendix further contains the complete database of identified abandoned villages together with all cases examined within the study region.

Most of the information regarding the abandoned villages has been obtained through historical documents or reviews/compilations thereof on topics such as earthquakes [22] or avalanches (e.g., [23]). In addition to synthesizing information from previously published studies, the database incorporates new evidence compiled during recent research on several abandoned settlements. This has made it possible to reconstruct in detail the abandonment trajectories of some villages that had previously received little scholarly attention, including cases such as Biuse.

Studied temporary coverage

During the study period from the year 1275 to 2024, in terms of climatic and historical context, two clearly separated periods can be distinguished: the LIA [1275–1850) and the IE [1850–2024]. These have been divided in this study into two sub-periods respectively: early LIA [1275 – 1540), late LIA [1540 – 1850), early IE [1850 – 1960), and late IE [1960 – 2024].

These subdivisions have been performed taking into account general climatic trends in the region for the LIA [18,24] and historical-demographic events mainly for the IE; the year 1960 has been selected because it exhibited a peak of exodus/migration from the countryside.

The temporal attribution of abandonment events is inherently affected by uncertainties associated with historical documentation. Previous studies have shown that temporal aggregation can influence the interpretation of spatiotemporal settlement patterns, potentially generating artificial trends or obscuring gradual processes [25]. Consequently, the chronological subdivision adopted here should be interpreted as an analytical framework rather than as sharply defined historical boundaries.

Criteria and categorization of the causes of abandonment

A village was classified as abandoned when it had lost all permanent residents, or retained at most a single genuine permanent inhabitant. Additional indicators of abandonment included the severe deterioration of most buildings and the discontinuation of traditional community activities, such as the annual village festival. Settlements that experienced substantial depopulation but never became completely uninhabited were excluded, as the study focused on cases of complete or near-complete abandonment leading to the effective disappearance of the original settlement core (extended methodological information is provided in the S1 Appendix).

For the present study, the causes of abandonment are classified into three categories: natural (geological, climate, and biological hazards), anthropogenic (socioeconomic and geopolitical/historical factors), and unknown, as summarized and exemplified in greater detail in Table 1.

Table 1. Summary of the typologies of abandonment causes identified in the analyzed villages and developed for this study.

	Cause of abandonment	**Examples / subcategories**
NATURAL HAZARDS	Geological hazards	Avalanches, earthquakes, landslides
	Climate hazards	Droughts, floods, frosts
	Biological hazards	Plagues, epidemics such as cholera or pests

ANTHROPOGENIC FACTORS	Socioeconomic factors	Rural exodus, access difficulties and lack of services, fires
	Geopolitical /historical factors	Wars and armed conflicts, the construction of dams
UNKNOWN	Unknown reasons	Little documentation

In some cases, abandonment resulted from a combination of natural hazards and anthropogenic factors (e.g., Sant Sebastià de Buseu, *El Pallars Sobirà*; S2 Appendix); these mixed causes were proportionally considered into both categories. In other cases, although both natural and anthropogenic factors were involved, only one was selected based on the ultimate abandonment or disappearance trigger. For example, in Montesquiu (*El Pallars Jussà*; S2 Appendix) depopulation began after farmland flooding caused by reservoir construction in 1918 (geopolitical/historical factors), but the abandonment date was recorded as 1962 because at least two inhabitants remained until the rural exodus of the 1960s began (socioeconomic factors).

Apart from cases where the abandonment cause could not be identified (unknown reasons), another limitation concerns cases in which the abandonment date could not be approximated, making their classification unfeasible.

Results

Magnitude and temporal patterns of village abandonment

The number of abandoned villages recorded in the database was 307 (Table 2 and Fig 1), out of 1,214 settlements identified. The average rate of abandoned villages per century is equal to 41, meaning that one village was abandoned every 2.4 years. Considering the total area studied (9,925.4 km²), in statistical terms the abandonment rate was 0.004 per century per square kilometre. The highest rate of village abandonment was observed during the late IE, followed by the early IE. Regarding the LIA, the abandonment rate per century and per km² in the first subperiod is twice that recorded in the second. No significant correlation was found between the number of abandoned villages and altitude for the entire period (Figs 1 and S3 Appendix). However, the abandonment of settlements located at higher altitudes occurred primarily during the early LIA.

Table 2. General summary of the number of documented abandoned villages organized by studied periods.

Period	Abandoned Villages	Abandoned Villages (%)	Abandoned Villages/ year	Abandoned Villages/ century
All Period [1275 - 2024]	307	100	0.4	41.0
LIA Early Period [1275 - 1540)	50	16.3	0.2	18.9
LIA Late Period [1540 - 1850)	23	7.5	0.1	7.4
IE Early Period [1850 - 1960)	60	19.5	0.6	55.0
IE Late Period [1960 – 2024]	174	56.7	2.7	271.9

Causes of abandonment

Across the full period of the study, socioeconomic factors clearly dominate the causes of village abandonment (66.3%), followed by geopolitical/historical drivers (11.9%). Unknown causes (9.1%) and geological hazards (6.8%) also represent notable proportions, whereas biological and climatic hazards account for 3.3% and 2.6%, respectively (Fig 2). Overall, anthropogenic factors explain 78.2% of documented cases, compared with 12.7% attributed to natural hazards.

Fig 2. Causes leading to disappearance or abandonment of villages across the full study period (1275–2024; a-b). Panels c-f show the contribution of the individual risks for each subperiod, while panels g-j group these into natural hazards, anthropogenic factors, and unknown causes. LIA: Little Ice Age; IE: Industrial Era.

The relative importance of these causes varies over time (Table 3). During the early LIA, socioeconomic factors and biological hazards were most prevalent, while the proportion of cases attributed to unknown causes was also notable (Fig 2c). In the late LIA, unknown causes account for a substantial share of abandonments, and geological hazards become more prominent (Fig 2d). In contrast, during the IE, socioeconomic factors overwhelmingly dominate, particularly in its later phase (Fig 2e–f). Overall, the relative contribution of natural hazards is higher during the LIA than during the IE, despite the lower absolute number of abandonment cases (Fig 2g–j).

Table 3. Quantitative summarize of the obtained cases of abandoned villages classified by causes.

Period	Geological Hazards	Climate Hazards	Biological Hazards	Total Natural Hazards	Socio-economic	Geopolitical/ Historical	Total Anthropogenic	Unknown
All Period [1275 - 2024]	21.0 (6.8%)	8.0 (2.6%)	10.0 (3.3%)	39.0 (12.7%)	203.5 (66.3%)	36.5 (11.9%)	240.0 (78.2%)	28.0 (9.1%)
LIA Early Period [1275 - 1540)	5.0 (10.0%)	1.5 (3.0%)	10.0 (20.0%)	16.5 (33.0%)	15.0 (30.0%)	4.5 (9.0%)	19.5 (39.0%)	14.0 (28.0%)
LIA Late Period [1540 - 1850)	7.0 (30.4%)	1.0 (4.3%)	0.0 (0.0%)	8.0 (34.8%)	2.0 (8.7%)	2.0 (8.7%)	4.0 (17.4%)	11.0 (47.8%)
IE Early Period [1850 - 1960)	6.0 (10.0%)	2.0 (3.3%)	0.0 (0.0%)	8.0 (13.3%)	35.0 (58.3%)	14.0 (23.3%)	49.0 (81.7%)	3.0 (5.0%)
IE Late Period [1960 – 2024]	3.0 (1.7%)	3.5 (2.0%)	0.0 (0.0%)	6.5 (3.7%)	151.5 (87.1%)	16.0 (9.2%)	167.5 (96.3%)	0.0 (0.0%)

Spatial patterns of village abandonment

Spatially, abandonment is unevenly distributed across the Catalan Pyrenees, with consistently higher rates observed in the western sector compared to the central and eastern regions. This spatial contrast is evident across the entire study period, with the western sector concentrating the majority of documented cases (Fig. 3).

Fig 3. Maps showing the abandoned villages documented in the current study for each studied period. LIA: Little Ice Age; IE: Industrial Era. The different colours of the dots indicate the typologies of causes of abandonment.

The intensity of the abandonment varies significantly at the regional scale, indicating that settlement decline is not spatially homogeneous. During the LIA, most documented cases are also concentrated in the western sector.

This spatial contrast is further reflected in county-level rates (S3 Appendix). The western sector shows the highest abandonment intensities, particularly in comarcas such as *L'Alta Ribagorça* and *El Pallars Jussà* (0.09 and 0.08 villages·century^{-1}·km^{-2}, respectively). In contrast, the central Catalan Pyrenees exhibit the lowest abandonment rates, especially in comarcas such as *La Cerdanya* and *El Berguedà*. The eastern sector displays intermediate values, with abandonment rates higher than in the central region but lower than in the western core.

The spatial distribution of abandonment is also associated with differences in the relative contribution of causes (Fig 4). In the western Catalan Pyrenees, where abandonment is most intense, natural hazards are more prominent during the LIA, particularly biological hazards linked to epidemic events and geological hazards (i.e., slope processes such as avalanches and landslides). Climate-related factors are also present, although more localized, particularly during the LIA. In contrast, anthropogenic factors dominate more clearly during the IE, especially socioeconomic factors related to reduced accessibility, agricultural decline, and rural depopulation processes. Geopolitical/historical factors are also documented, mainly associated with armed conflicts and the construction of large infrastructures, including reservoirs. In the central and eastern sectors, where abandonment rates are lower, anthropogenic factors predominate, with fewer cases linked to natural hazards.

Fig 4. Representation of the causes of village abandonment over time for all cases (a) and for each county (b–i). LIA: Little Ice Age; IE: Industrial Era.

This spatial gradient is consistent with the concentration of high-altitude and more isolated settlements in the western Pyrenees. Overall, these spatial differences indicate that abandonment processes were strongly structured at the regional scale and influenced by a combination of geographical, environmental, geopolitical, historical and socioeconomic conditions. Detailed regional patterns and county-level analyses are provided in the Supporting Information (S2 Appendix_Table S1 and S3 Appendix).

Discussion

Regional contrasts in village abandonment across the Catalan Pyrenees

Western part of the Catalan Pyrenees

This sector exhibits the highest incidence of village abandonment, with 259 cases out of the 307 recorded in the study. In the counties with the highest levels of abandonment, *El Pallars Jussà* and *L'Alt Urgell*, the most frequent cases occurred during the late IE and were primarily driven by socioeconomic factors. During the early part of the LIA, rate abandonments ranged between (0.8-6.8 abandonments/century) and during the late part, between (0-2.3 abandonments/century). Thus, the abandonment rate during early LIA was 2.5 times higher than during the late part (0.18 and 0.07 abandonments/century).

The abandonment of the highest-elevation villages, corresponding to the Western Catalan Pyrenees, occurred primarily during the early LIA. This spatial pattern reflects the general west-to-east decrease in elevation across the Catalan Pyrenees (Fig. 3). Among natural hazards in the western sector, biological and geological hazards were the most prominent, depending on the county (Fig 4b–g and S3 Appendix). As far as current research allows, biological hazards were mostly attributable to the impact of the Black Death in the 14th century, particularly in the counties *of La Val d'Aran*, *El Pallars Sobirà*, *La Noguera*, and *L'Alt Urgell* (e.g., [26,27]).

Geological hazards during the early LIA mainly corresponded to avalanches in *La Val d'Aran, El Pallars Sobirà*, and *L'Alta Ribagorça* (e.g., [23,28]). The devastating effects of the earthquake on 3 March 1373 in *La Noguera* are also noteworthy([29]. Regarding socioeconomic factors, they primarily caused village abandonment in the county of *La Noguera*, as well as in *L'Alta Ribagorça*, *El Pallars Jussà*, and *El Pallars Sobirà*. Most of these cases are associated with changes in the organization of livestock farming and the structuring of the Pyrenean Mountain territory (e.g., [30]). Geopolitical/historical reasons for abandonment were mainly related to wars and banditry [31].

During the late LIA, natural hazards were predominantly geological, particularly avalanches, with counties such as *La Val d'Aran* and *El Pallars Sobirà* being the most affected. Some village abandonments caused by avalanches were occasionally followed by the relocation of the settlement (e.g., Àrreu in *El Pallars Sobirà*), while in other cases, the villages were rebuilt on the same site (e.g., Senet in *L'Alta Ribagorça*). Although avalanche hazard remains a characteristic feature of many Pyrenean valleys today, these historical events may also reflect a gradual process of adaptation, whereby settlements were increasingly relocated or rebuilt outside the most avalanche-prone areas as local knowledge of the hazard accumulated.

Regarding anthropogenic factors, socioeconomic causes followed the same patterns observed during the early LIA, whereas geopolitical/historical factors continued to be predominantly associated with armed conflicts. Throughout the LIA, the Western Catalan Pyrenees experienced recurrent episodes of warfare, ranging from late medieval succession disputes and incursions by the Count of Foix to the War of Pallars and, later, the War of the Spanish Succession.

During the early IE, most natural forcings were also geological, with avalanches in *La Val d'Aran* being particularly notable. Socioeconomic factors were primarily related to lack of accessibility and services, the influence of major settlements, subsistence practices, infrastructure and difficult access, as well as some cases of activity cessation, such as those resulting from the construction of the tunnel in *La Val d'Aran*. Geopolitical/historical factors were mainly associated with the Spanish Civil War and the construction of dams during the 20th century, which directly flooded settlements or agricultural lands.

During the late IE, and as previously noted, socioeconomic factors predominated (Fig 2e). Most cases were associated with difficult conditions, including migration in the 1970s to areas with greater economic opportunities, lack of accessibility and services, and the rural exodus that began primarily in the 1960s following the introduction of tractors and the decline of manual reaping. Mechanization of agriculture and progressive industrialization also contributed, as did the cessation of economic activities such as mining or dam construction. In more recent years, socioeconomic abandonment has been observed among families aged 40–50, often driven by the absence of nearby higher education opportunities for their children. Additionally, some cases were attributable to geopolitical/historical factors, such as the construction of reservoirs.

Central Catalan Pyrenees

The Central Catalan Pyrenees exhibited the lowest abandonment rates, with 16 cases out of the 307 recorded in the study. No abandonments due to natural forcings were identified, and those occurring during the LIA were scarce (Fig 4h–i and S3 Appendix). It should be noted that some deserted settlements from this period are documented; however, the information is so limited that they could not be included in the database of the present study ([32]; S2 Appendix).

Regarding anthropogenic factors, socioeconomic factors were predominant, mainly associated with difficult living conditions and the cessation of mining activities (*El Berguedà*), primarily occurring from the 1960s onward. In *La Cerdanya*, the construction of the Tunel del Cadí also led to some abandonments that can be assigned to geopolitical/historical factors.

Eastern part of the Catalan Pyrenees

In the eastern part, abandonment rates were low but relatively higher than in the central region, with 32 cases out of the 307 recorded in the study. Only two cases were attributable to natural forcings, both occurring during the early LIA. These correspond to geological factors and resulted from the effects of the 14 February 1428 earthquake in *El Ripollès*, which also affected numerous locations in Catalonia (e.g., [22]).

Anthropogenic factors were primarily related to socioeconomic causes and correspond to abandonments during the late IE in the three counties of this area, as well as during the late IE in *El Ripollès* (Fig 4j–l and S3 Appendix). These abandonments were largely linked to the vegetal coal crisis of the 1960s–1970s in *L'Alta Garrotxa*, which led to a certain degree of rural exodus, with farmers migrating to factories [33]. It is also worth highlighting the boom in coastal tourism (relatively close to the *L'Alta Garrotxa*), which increased the availability of significantly better wages and working conditions—advantages with which the primary sector could not compete.

Temporal variability in anthropogenic and natural causes of village abandonment

The results of this study reveal substantial temporal variability in the factors driving village abandonment in the Catalan Pyrenees (Fig. 2). Although anthropogenic factors account for the majority of documented abandonment cases over the full study period [1275–2024], representing 78.2% of all records, this overall dominance masks important differences between historical periods.

During the LIA, abandonment processes were characterized by a relatively heterogeneous combination of anthropogenic factors, natural hazards, with a higher proportion of unknown causes. In the early LIA, the relative contributions of anthropogenic factors (39.0%) and natural hazards (33.0%) were broadly comparable, whereas during the late LIA natural hazards (34.8%) exceeded anthropogenic factors (17.4%). This pattern suggests that environmental pressures played a more prominent role during the LIA than in subsequent periods (Figs 2 and 3). Similar interactions between climatic stress, environmental hazards, and rural adaptation have been documented in pastoral regions elsewhere in Europe during the LIA [7]. Our data point out that among natural hazards, geological and biological hazards were particularly relevant. Avalanches represented the most common geological cause of abandonment in high-mountain areas, while biological hazards were largely associated with the demographic consequences of epidemic outbreaks, particularly the Black Death and its aftermath. Climatic risks also contributed to abandonment processes, although their direct influence remained comparatively limited throughout the study period. At the same time, anthropogenic factors of abandonment during the LIA were primarily linked to local socioeconomic constraints associated with mountain subsistence systems, while geopolitical/historical disturbances, including warfare and insecurity, contributed to settlement decline in specific periods.

A marked transition occurred during the IE, when anthropogenic factors became overwhelmingly dominant, increasing from 81.7% of abandonment cases during the early IE to 96.3% during the late IE. In contrast, the contribution of natural hazards declined to between 13.3% and 3.7% (Fig. 2). During this period, socioeconomic factors emerged as the principal causes of abandonment, reflecting structural transformations that affected mountain regions throughout southern Europe. These processes included declining accessibility, the progressive collapse of subsistence-based agricultural systems, agricultural mechanization, and increasing migration towards urban and industrial centres. Similar processes have been documented in other European mountain regions during contemporary periods, including the rest of Pyrenees and the Alps, where industrialization, unequal spatial development, the decline of traditional farming systems, and the concentration of economic opportunities in accessible lowland and urban areas contributed to sustained depopulation and the abandonment of marginal settlements [34,35]. Contemporary studies conducted beyond Europe likewise show that accessibility, service provision, housing conditions, and economic opportunities frequently outweigh environmental constraints in shaping decisions to leave rural settlements [36,37].

During IE, geopolitical/historical factors also contributed to abandonment dynamics, particularly through armed conflicts (Spanish Civil War; 1936-1939) and the construction of large infrastructures such as reservoirs, which displaced local populations and transformed traditional land-use systems. By comparison, geological, biological, and climatic hazards became increasingly marginal as direct causes of settlement abandonment over the IE.

Overall, these results indicate a transition shaped by the interaction of environmental pressures, local socioeconomic constraints, and historical disturbances during the LIA, to processes increasingly dominated by large-scale socioeconomic transformations during the IE. This temporal variability sets the basis for interpreting the role of climate within these abandonment processes.

Climate variability: trigger, driver, or vulnerability multiplier?

Although climate was directly identified as the cause of abandonment in only 2.6% of the documented cases, its influence appears to have been more widespread than suggested by the raw data (i.e., by direct attribution alone). Climate is explicitly mentioned in 12.4% of abandonment narratives (38 out of 307 in total) and may have contributed, either directly or indirectly, to approximately 15% of all abandonment processes. The documentary sources analyzed in this study describe floods, prolonged snowfall, severe winters, permanent snow cover, low-temperature episodes, and even lightning strikes as factors affecting settlement viability. For example, persistent snow cover and severe winter conditions were documented as contributing factors in the abandonment of Bausén (*La Val d'Aran*), while floodings are mentioned in several villages of the western Pyrenees (i.e. Artiga and the old Pont de Bar, *La Val d'Aran*). In other cases, climate was not recorded as the immediate cause of abandonment but likely contributed to other natural events such as avalanches or rainfall-induced landslides. Examples include Àrreu (*Pallars Sobirà*) and villages in La Val d'Aran affected by destructive avalanche activity (i.e. Cassinhau and Corilha; [23]), where climatic conditions likely acted as a predisposing factor rather than as the direct trigger of abandonment.

This broader climatic influence is particularly relevant in the context of the LIA, a period characterized by increased climatic variability and a general cooling trend across both hemispheres [38]. In the Iberian region, numerous studies have documented colder conditions together with a higher frequency of extreme hydroclimatic events, including intense rainfall episodes and floods [17,18,39–41]. These climatic conditions have been linked to a combination of external forcings, including the Wolf, Spörer, Maunder, and Dalton solar minima [42], changes in thermohaline circulation [43], clusters of volcanic eruptions [44], and fluctuations in large-scale atmospheric circulation patterns such as the North Atlantic Oscillation [24,45]. Furthermore, some biological crises documented during the LIA may also have been influenced by the climatic conditions [6]. Within this climatic framework, the proportion of abandonment cases directly or indirectly associated with climate was higher during the LIA than during the IE, reaching its maximum during the late LIA, when climate acted as trigger in the 4.4% of the cases. Furthermore, abandonment peaks frequently occurred after periods of climatic deterioration, particularly during the severe phase identified between 1300 and 1480 and around the cooling episodes centred on ~1450 and ~1610 (Fig. 5). While these correspondences do not demonstrate causality, they indicate that climatic stress formed part of the broader environmental context in which abandonment processes developed, likely increasing the vulnerability of mountain communities.

Fig 5. Cases of disappeared, abandoned or unhabitated villages in the Catalan Pyrenees [1275-2024] and climate variability records selection in northern Iberian Peninsula. The panels summarize reconstructed relative temperature [46], speleothem δ^{18}O records [18], extreme flood frequency [47], Mediterranean Oscillation Index [40], and the number of disappeared, abandoned, or uninhabited villages due to Anthropogenic, Natural, or Unknown causes (gold, green and grey records, respectively; this study). Shaded areas indicate periods of major climate irregularities defined in the Iberian Mountains for the LIA by [17]. Climate features are expresses in black squares. Historical events, socioeconomic crises and natural hazards are also annotated. Arrows in the records indicate moments with higher number of villages abandonment. Years are expressed as Common Era years (CE). LIA: Little Ice Age; IE: Industrial Era.

Importantly, the documentary sources rarely portray climate as an isolated cause of abandonment. In most cases, adverse climatic conditions interacted with pre-existing geographical, economic, and demographic constraints, contributing to settlement decline without constituting the sole triggering factor. The case of Sant Sebastià de Buseu, which in 1962 was completely abandoned, illustrates this pattern particularly well. There, persistent snowfall, strong winds, and severe winter conditions intensified the difficulties associated with high altitude, poor accessibility, and increasing socioeconomic marginalization. Similar interactions are likely to have operated in other settlements where environmental pressures compounded existing structural vulnerabilities. This interpretation aligns with recent studies emphasizing that societal crises rarely result from single drivers but emerge from interacting environmental, economic, political, and demographic pressures. Several abandonment cases identified in this study can therefore be understood as outcomes of interacting stressors, consistent with the "polycrisis" framework applied to historical societal transformations [8].

Taken together, these findings suggest that climate variability functioned primarily as a vulnerability multiplier. This interpretation is consistent with recent studies emphasizing that the impacts of climatic fluctuations were contingent upon specific historical and social contexts, rather than being direct or deterministic drivers of societal change [48,49]. It is also agreement with studies from remote upland site in Northern Ireland covering the last millennium, which similarly identify climate as a contributing factor operating through existing societal vulnerabilities rather than as an independent cause of disruption [50]. Thus, rather than acting as a dominant driver, climatic stress increased exposure to environmental hazards while simultaneously reducing the capacity of mountain communities to cope with structural constraints. In this sense, climate was only occasionally a direct trigger and rarely the principal driver of abandonment; however, it frequently contributed to the conditions under which abandonment became more likely.

From environmentally constrained systems to socioeconomic abandonment

Beyond the temporal variability in abandonment drivers, the results point to a broader transformation in the socio-ecological systems governing settlement persistence and abandonment between the LIA and the IE.

This transition is reflected both temporally and spatially. During the LIA, abandonment was concentrated in the western Catalan Pyrenees, where high-elevation settlements were more exposed to environmental constraints and isolation. In contrast, the central sector shows consistently low abandonment rates, while the eastern Pyrenees are characterized by abandonment trajectories more strongly linked to twentieth-century economic transformations.

The pronounced west-to-east gradient highlights the strong role of geographical context in shaping settlement vulnerability. The western Pyrenees concentrated most abandonment cases, particularly during the LIA, due to the combined effects of altitude, remoteness, environmental risk, and limited economic diversification. Notably, some high-elevation villages were already abandoned during the early LIA for socioeconomic reasons, indicating that environmental marginality alone cannot explain abandonment and that broader demographic and economic dynamics were already at play

During the LIA, settlement persistence depended on the ability of communities to cope with multiple interacting local stressors. Environmental hazards, climatic variability, demographic crises, geographical isolation, and economic limitations combined to produce highly vulnerable systems, in which abandonment resulted from the cumulative effects of these constraints rather than from a single cause. In addition to these long-term processes, the early stages of the LIA coincided with the fourteenth-century crisis, which affected large parts of Europe through the combined impacts of demographic decline, epidemic outbreaks, economic disruption, and environmental stress. Recent studies increasingly emphasize the contribution of extreme weather events and natural hazards to the broader agrarian and societal transformations of this period [8,51–53]. Several abandonment cases documented in the Catalan Pyrenees may have developed within this wider context of regional instability. Notably, most fourteenth-century abandonment cases identified in this study are associated with biological hazards (n = 5) or remain of unknown cause (n = 7), while only a smaller number are linked to socioeconomic factors (n = 2). Although these results do not allow a direct attribution to the fourteenth-century crisis, they are compatible with a scenario in which epidemic mortality, environmental stress, and other interacting pressures contributed to weakening the resilience of mountain communities and increasing the likelihood of abandonment.

Regarding the IE, a contrasting pattern emerged. Although environmental conditions continued to shape mountain life, abandonment became increasingly decoupled from local environmental constraints and more strongly linked to large-scale socio-economic transformations. Processes such as agricultural modernization, industrialization, improved transportation, and rural-to-urban migration progressively undermined the demographic and economic viability of traditional mountain settlements. These patterns are consistent with findings from other regions of the world, where factors such as accessibility, availability of services, housing quality, and access to employment opportunities have often proven more influential than environmental constraints in shaping rural outmigration and settlement abandonment [36,37].

These transformations during the IE took different forms across the Catalan Pyrenees. In the western Pyrenees, abandonment was closely linked to agricultural mechanization, the decline of subsistence-based economies, and the rural exodus of the 1960s and 1970s. In the central sector, the closure of mining activities contributed to village decline, whereas in the eastern Pyrenees the charcoal crisis of the 1960s–1970s in *L'Alta Garrotxa* accelerated outmigration toward industrial employment and coincided with the growing attraction of coastal tourism opportunities [33].

Importantly, these socioeconomic drivers differed substantially from those operating during the LIA. In this period socioeconomic drivers were mainly associated with local-scale processes, including changes in pastoral organization, the restructuring of traditional mountain territorial systems [30], demographic crises, and the limited adaptive capacity of isolated mountain communities. By contrast, abandonment during the IE increasingly reflected external economic forces acting at regional and national scales. In the Catalan Pyrenees, this implies that, by the twentieth century, settlement viability depended primarily on the capacity of communities to remain connected to wider economic and infrastructural systems.

The temporal evolution of abandonment patterns therefore suggests a progressive shift from environmentally constrained systems towards socio-economically driven abandonment processes. Consequently, the transition from the LIA to the IE should not be understood merely as a change in abandonment rates, but rather as a fundamental transformation in the mechanisms governing settlement persistence and decline. Whereas environmental conditions and geographical marginality played a major role in shaping vulnerability during the LIA, socioeconomic opportunities, accessibility, and regional development dynamics became the dominant determinants of abandonment during the IE.

Adaptation, resilience and implications for contemporary climate change

The long-term perspective provided by this study highlights the notable resilience of mountain communities in the Catalan Pyrenees. Despite colder temperatures and increased climatic variability during the LIA, many settlements persisted for centuries under environmental conditions more severe than those experienced today, indicating a substantial capacity for long-term adaptation. Similar patterns have been identified in other European marginal environments, where communities maintained settlement continuity despite climatic downturns and demographic crises, either by effectively buffering environmental stress or by recovering rapidly from disturbances [50].

However, this resilience was not unlimited. Abandonment typically occurred when climatic stress interacted with other forms of vulnerability, including geographical isolation, demographic decline, economic marginalization, and political instability. In this sense, climate acted less as a direct driver than as a factor amplifying existing fragilities, reducing the capacity of communities to maintain viable settlement systems. This interpretation aligns with growing evidence that the societal consequences of climatic events depend strongly on local socio-environmental conditions, including resource availability, institutional frameworks, and social networks, which shape both vulnerability and resilience to environmental stress [54]. The same climatic event may therefore produce contrasting outcomes depending on local adaptive capacity and socioeconomic conditions [8].

At the same time, historical evidence suggests that communities actively adapted to climatic pressures through changes in land-use and subsistence strategies. In pastoral regions of north-west Europe, for example, small-scale shifts in agricultural practices have been interpreted as adaptive responses to increased climatic variability during the LIA, aimed at reducing risk and buffering food supply [7]. More broadly, socio-ecological research across different temporal and geographical contexts indicates that communities can reorganize settlement patterns, resource use, and social systems in response to environmental instability, thereby maintaining long-term continuity despite significant ecological change [10]. Such adaptive flexibility likely contributed to the persistence of many mountain settlements under adverse environmental conditions

These findings provide important insights for understanding the impacts of contemporary climate change. The data derived from the documentary sources analyzed in this study indicates that the main risk lies not in climate variability alone, but also in its interaction with pre-existing socioeconomic vulnerabilities. Mountain regions currently facing depopulation, ageing populations, declining services, and economic marginalization may therefore be particularly sensitive to future climatic stressors [48].

At the same time, direct comparisons between the LIA and present-day climate change should be made with caution. While past climatic shifts unfolded over long time scales that allowed gradual adaptation, current warming is occurring at an unprecedented rate [38], potentially exceeding the adaptive capacity of both communities and ecosystems.

Importantly, the history of village abandonment also shows that depopulation is not an inevitable response to environmental change. Settlement persistence depends on adaptive capacity, including accessibility, economic diversification, and institutional support. Strengthening these factors may therefore enhance the resilience of mountain regions under future climate scenarios and contribute to more sustainable socio-ecological systems.

Paradoxically, some mountain regions that experienced severe depopulation during the twentieth century may gain renewed strategic importance under future warming scenarios, owing to their cooler climatic conditions, water resources, and the wide range of ecosystem services they provide [4].

Beyond local adaptive capacity, long-term resilience will also depend on the existence of supportive institutional frameworks. The research of González-Moreno et al., 2025 across European mountain regions highlights that vulnerability is shaped not only by environmental change, but also by demographic decline, land abandonment, limited service provision, and reduced economic opportunities. Effective adaptation therefore requires coordinated policies capable of strengthening local economies, improving accessibility, supporting essential services, and facilitating the implementation of context-specific adaptation measures. In this context, emerging forms of "new ruralities" may offer opportunities to revitalize some mountain areas through new economic activities, changing residential preferences, and stronger links between rural and urban systems. However, their long-term success will likely depend on sustained institutional support and governance mechanisms that enhance both social and ecological resilience in mountain regions. In the Catalan and Aranese Pyrenees, these opportunities are particularly relevant given the scale of long-term settlement decline documented in this study. Of the 1,214 settlements identified, 307 (25.3%) are currently abandoned, representing not only a substantial loss of cultural and historical heritage but also a significant territorial legacy. Far from being viewed solely as symbols of decline, some of these abandoned villages may constitute valuable assets for future rural revitalisation initiatives, supporting new forms of habitation, economic diversification, and landscape management in mountain areas. The future of mountain regions will therefore depend not only on their capacity to adapt to climate change, but also on society's willingness to invest in the social, economic, and institutional conditions that make adaptation possible.

Conclusion

Popular discourse often assumes that the more extreme climatic conditions of the LIA directly caused widespread village abandonment in mountain regions. However, the results of this study challenge this assumption. The strong geographical diversity of the Eastern Pyrenees (Catalan and Aranese sector) generated substantial environmental heterogeneity, meaning that climatic conditions—and their impacts—varied considerably between valleys and regions.

Over the study period [1275–2024], a total of 307 villages were abandoned out of 1,214 documented settlements, representing 25.3% of the total, equivalent to an average of 2.4 abandonment events per year. These figures highlight the magnitude of settlement decline in mountain environments and the associated loss of cultural and historical heritage.

Abandonment rates peaked during the IE, particularly in its later phase, whereas rates during the LIA were comparatively lower. These findings indicate that village abandonment cannot be primarily attributed to climatic deterioration, even during periods of increased environmental stress.

Instead, the results show that anthropogenic factors overwhelmingly dominated abandonment processes, accounting for 78.2% of cases. While natural hazards played a more significant role during the LIA, their overall influence remained secondary. Climatic factors were rarely recorded as direct triggers, but they contributed to approximately 15% of abandonment cases, often interacting with other stressors.

Despite the harsher environmental conditions of the LIA, many settlements persisted for centuries, demonstrating a notable capacity for adaptation. This resilience was likely supported by localized subsistence economies, flexible resource use, and forms of territorial self-organization.

The transition from the LIA to the IE reflects a fundamental shift in the drivers of abandonment. While environmental and geographical constraints played a key role in shaping vulnerability during the LIA, abandonment during the IE was increasingly driven by large-scale socioeconomic transformations, such as rural depopulation, declining accessibility, and the concentration of opportunities in urban areas. In this sense, Pyrenean communities proved capable of adapting to environmental pressures over long time scales, but were less able to respond to rapidly changing socioeconomic dynamics.

These findings suggest that climate variability acted primarily as a vulnerability multiplier rather than as a direct driver of abandonment. This conclusion also highlights the challenges inherent in reconstructing climate–society relationships, as environmental pressures rarely operated in isolation and were instead mediated by demographic, economic, geographical, and social conditions [48,49].

The historical experience of the Catalan and Aranese Pyrenees indicates that the risk under contemporary climate change lies not only in climate itself, but also in its interaction with existing socioeconomic fragilities. Mountain regions currently facing demographic decline, ageing populations, and reduced services may therefore be particularly sensitive to future climatic stress. Finally, the persistence and eventual abandonment of these settlements highlight both the resilience and the vulnerability of mountain socio-ecological systems. The loss of villages represents not only a demographic transformation but also a significant erosion of cultural and historical heritage. Understanding the conditions that allowed some communities to persist while others declined may provide valuable insights for enhancing the resilience of mountain regions in the context of ongoing global change.

Beyond their demographic significance, the abandonment of 307 out of the 1,214 documented settlements (25.3%) entails a substantial loss of cultural and historical heritage in the Catalan and Aranese Pyrenees. In regions such as the Pyrenees, which are currently facing high risks of depopulation [55], understanding the long-term drivers of settlement decline may contribute to informing strategies aimed at enhancing rural resilience. Improving land management and maintaining active landscapes may contribute to both climate change mitigation and adaptation [56,57]. At the same time, recent studies highlight that the vulnerability of mountain regions is shaped not only by environmental change but also by demographic trends, service provision, accessibility, and economic opportunities [4]. Paradoxically, some mountain areas that experienced severe depopulation during the twentieth century may gain renewed strategic importance under future warming scenarios owing to their cooler climatic conditions, water resources, and ecosystem services. However, realizing these opportunities will require supportive institutional frameworks and policies capable of strengthening adaptive capacity, reducing socio-economic vulnerability, and fostering emerging forms of "new ruralities" that contribute to long-term social and ecological resilience.

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Supporting Information

S1 Appendix. Extended information on methodological aspect. (PDF)

S2 Appendix. Database of the abandoned villages in the Eastern Pyrenees for the period 1275-2024. (XLSX)

S3 Appendix. Regional and county-level analysis of abandonment patterns (PDF).

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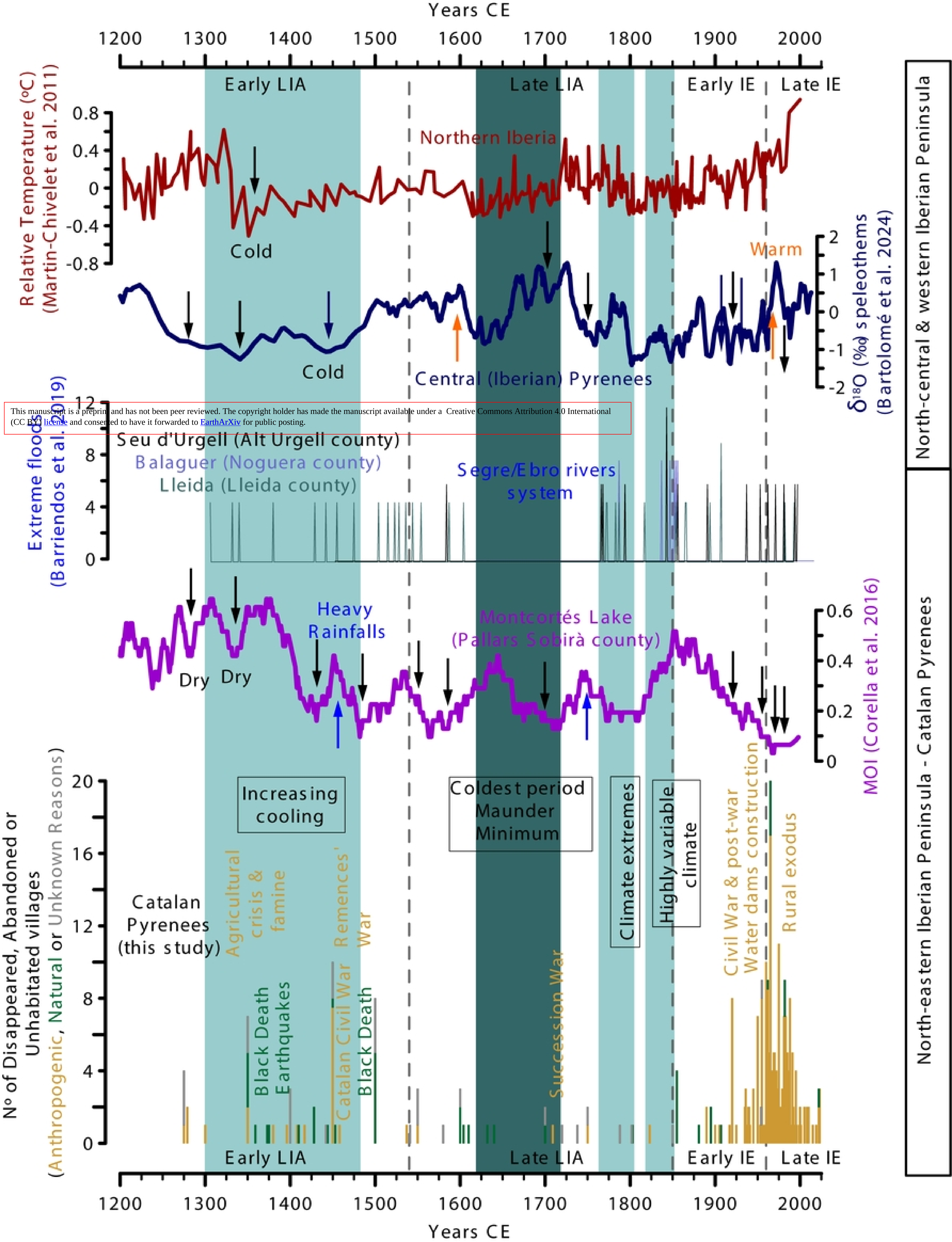

Years CE
Early LIA
Late LIA
Early IE
Late IE
Relative Temperature (ºC) (Martin-Chivelet et al. 2011)
Northern Iberia
Cold
Warm
δ18O (‰) speleothems (Bartolomé et al. 2024)
Central (Iberian) Pyrenees
North-central & western Iberian Peninsula
Extreme floods (Barriendos et al. 2019)
Seu d'Urgell (Alt Urgell county)
Balaguer (Noguera county)
Lleida (Lleida county)
Segre/Ebro rivers system
Dry
Heavy Rainfalls
Montcortés Lake (Pallars Sobirà county)
MOI (Corella et al. 2016)
Increasing cooling
Coldest period Maunder Minimum
Climate extremes
Highly variable climate
Nº of Disappeared, Abandoned or Unhabitated villages (Anthropogenic, Natural or Unknown Reasons)
Catalan Pyrenees (this study)
Agricultural crisis & famine
Remences' War
Black Death
Earthquakes
Catalan Civil War
Succession War
Civil War & post-war
Water dams construction
Rural exodus
North-eastern Iberian Peninsula - Catalan Pyrenees

Fig 5

Abandoned villages in the Catalan Pyrenees and the Aran Valley

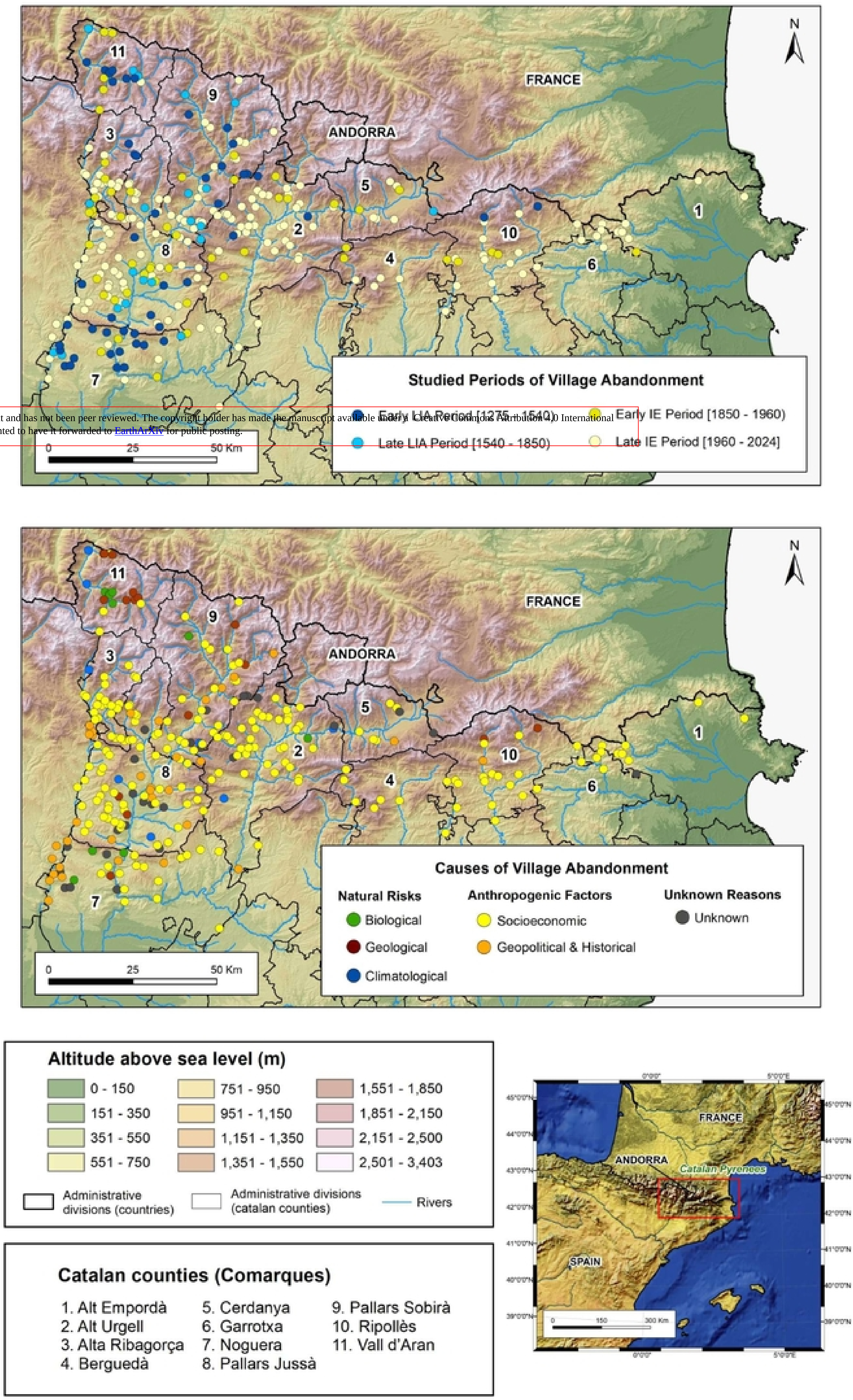
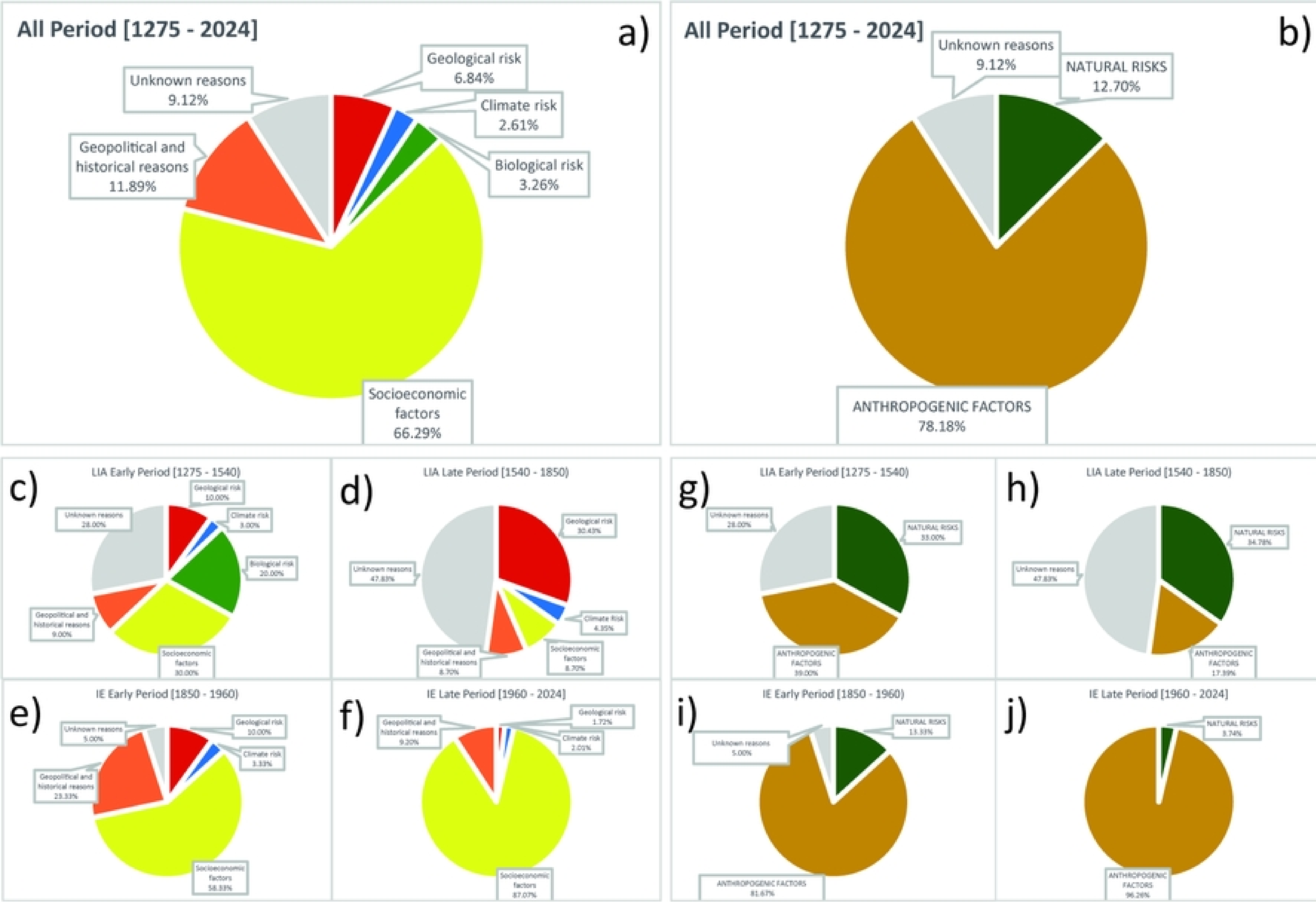
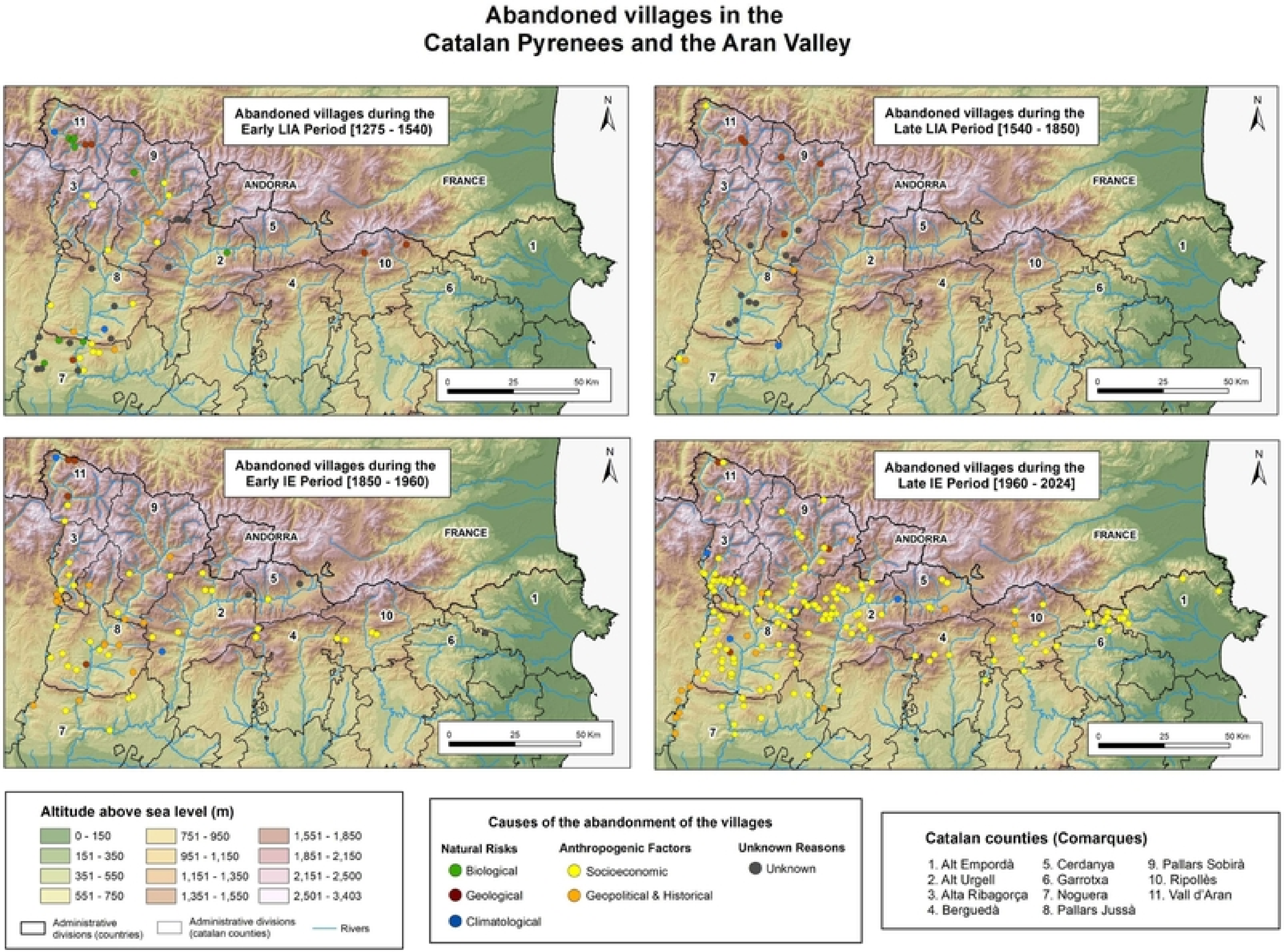


Fig 1



All Period [1275 - 2024]
a)
Geological risk
6.84%
Climate risk
2.61%
Biological risk
3.26%
Unknown reasons
9.12%
Geopolitical and historical reasons
11.89%
Socioeconomic factors
66.29%
All Period [1275 - 2024]
b)
Unknown reasons
9.12%
NATURAL RISKS
12.70%
ANTHROPOGENIC FACTORS
78.18%
c)
LIA Early Period [1275 - 1540)
Geological risk
10.00%
Climate risk
3.00%
Unknown reasons
28.00%
Biological risk
20.00%
Geopolitical and historical reasons
9.00%
Socioeconomic factors
30.00%
d)
LIA Late Period [1540 - 1850)
Geological risk
30.43%
Unknown reasons
47.83%
Climate Risk
4.35%
Geopolitical and historical reasons
8.70%
Socioeconomic factors
8.70%
e)
IE Early Period [1850 - 1960)
Unknown reasons
5.00%
Geological risk
10.00%
Climate risk
3.33%
Geopolitical and historical reasons
23.33%
Socioeconomic factors
58.33%
f)
IE Late Period [1960 - 2024]
Geopolitical and historical reasons
9.20%
Geological risk
1.72%
Climate risk
2.01%
Socioeconomic factors
87.07%
g)
LIA Early Period [1275 - 1540)
Unknown reasons
28.00%
NATURAL RISKS
33.00%
ANTHROPOGENIC FACTORS
39.00%
h)
LIA Late Period [1540 - 1850)
NATURAL RISKS
34.78%
Unknown reasons
47.83%
ANTHROPOGENIC FACTORS
17.39%
i)
IE Early Period [1850 - 1960)
NATURAL RISKS
13.33%
Unknown reasons
5.00%
ANTHROPOGENIC FACTORS
81.67%
j)
IE Late Period [1960 - 2024]
NATURAL RISKS
3.74%
ANTHROPOGENIC FACTORS
96.26%

Fig 2



Abandoned villages in the
Catalan Pyrenees and the Aran Valley
Abandoned villages during the
Early LIA Period [1275 - 1540]
Abandoned villages during the
Late LIA Period [1540 - 1850]
Abandoned villages during the
Early IE Period [1850 - 1960]
Abandoned villages during the
Late IE Period [1960 - 2024]
ANDORRA
FRANCE
N
0
25
50 Km
Altitude above sea level (m)
0 - 150
151 - 350
351 - 550
551 - 750
751 - 950
951 - 1,150
1,151 - 1,350
1,351 - 1,550
1,551 - 1,850
1,851 - 2,150
2,151 - 2,500
2,501 - 3,403
Administrative divisions (countries)
Administrative divisions (catalan counties)
Rivers
Causes of the abandonment of the villages
Natural Risks
Biological
Geological
Climatological
Anthropogenic Factors
Socioeconomic
Geopolitical & Historical
Unknown Reasons
Unknown
Catalan counties (Comarques)
1. Alt Empordà
2. Alt Urgell
3. Alta Ribagorça
4. Berguedà
5. Cerdanya
6. Garrotxa
7. Noguera
8. Pallars Jussà
9. Pallars Sobirà
10. Ripollès
11. Vall d'Aran

Fig 3

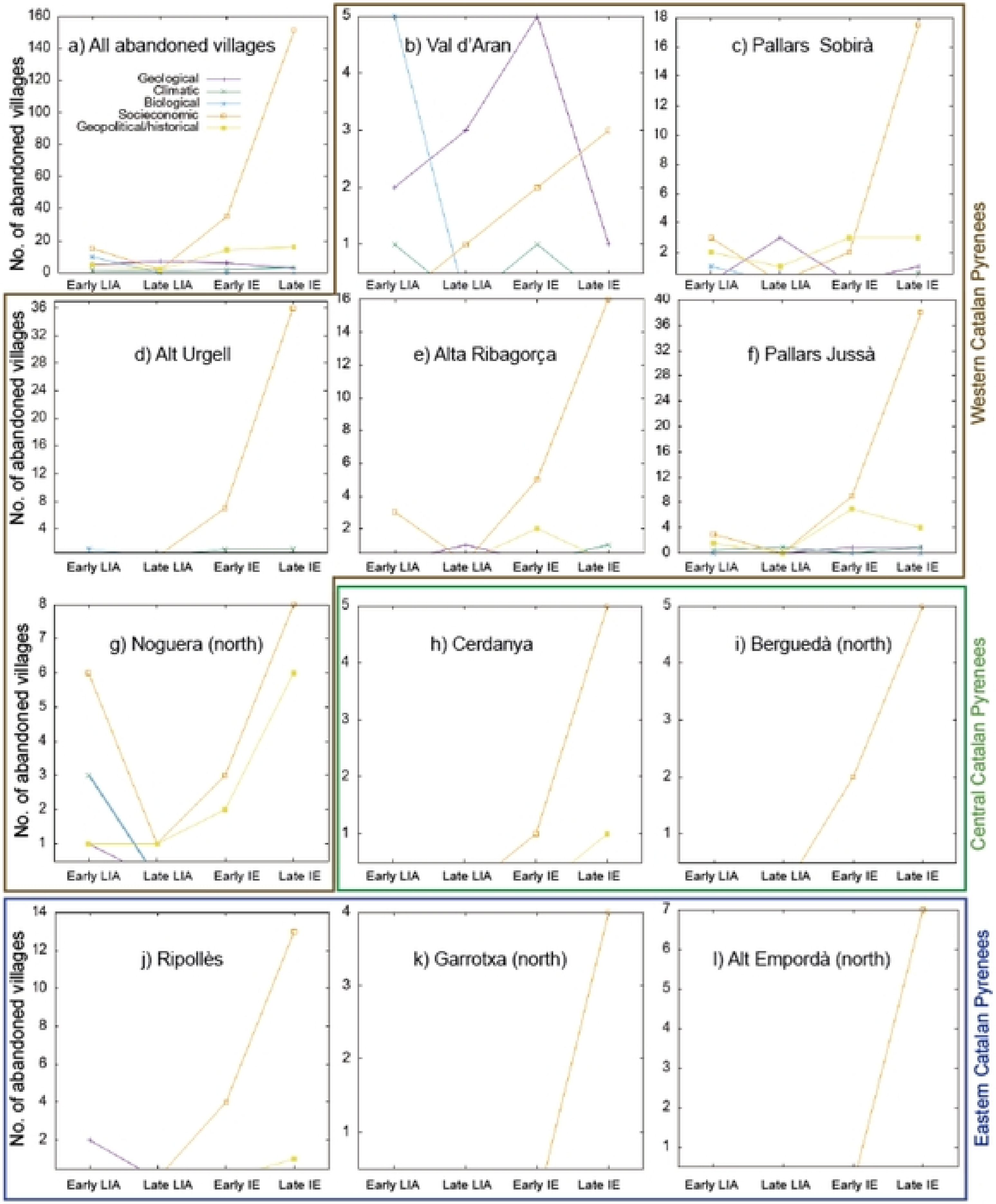

a) All abandoned villages
Geological
Climatic
Biological
Socieconomic
Geopolitical/historical
b) Val d'Aran
c) Pallars Sobirà
d) Alt Urgell
e) Alta Ribagorça
f) Pallars Jussà
g) Noguera (north)
h) Cerdanya
i) Berguedà (north)
j) Ripollès
k) Garrotxa (north)
l) Alt Empordà (north)
No. of abandoned villages
Early LIA
Late LIA
Early IE
Late IE
Western Catalan Pyrenees
Central Catalan Pyrenees
Eastern Catalan Pyrenees

Fig 4

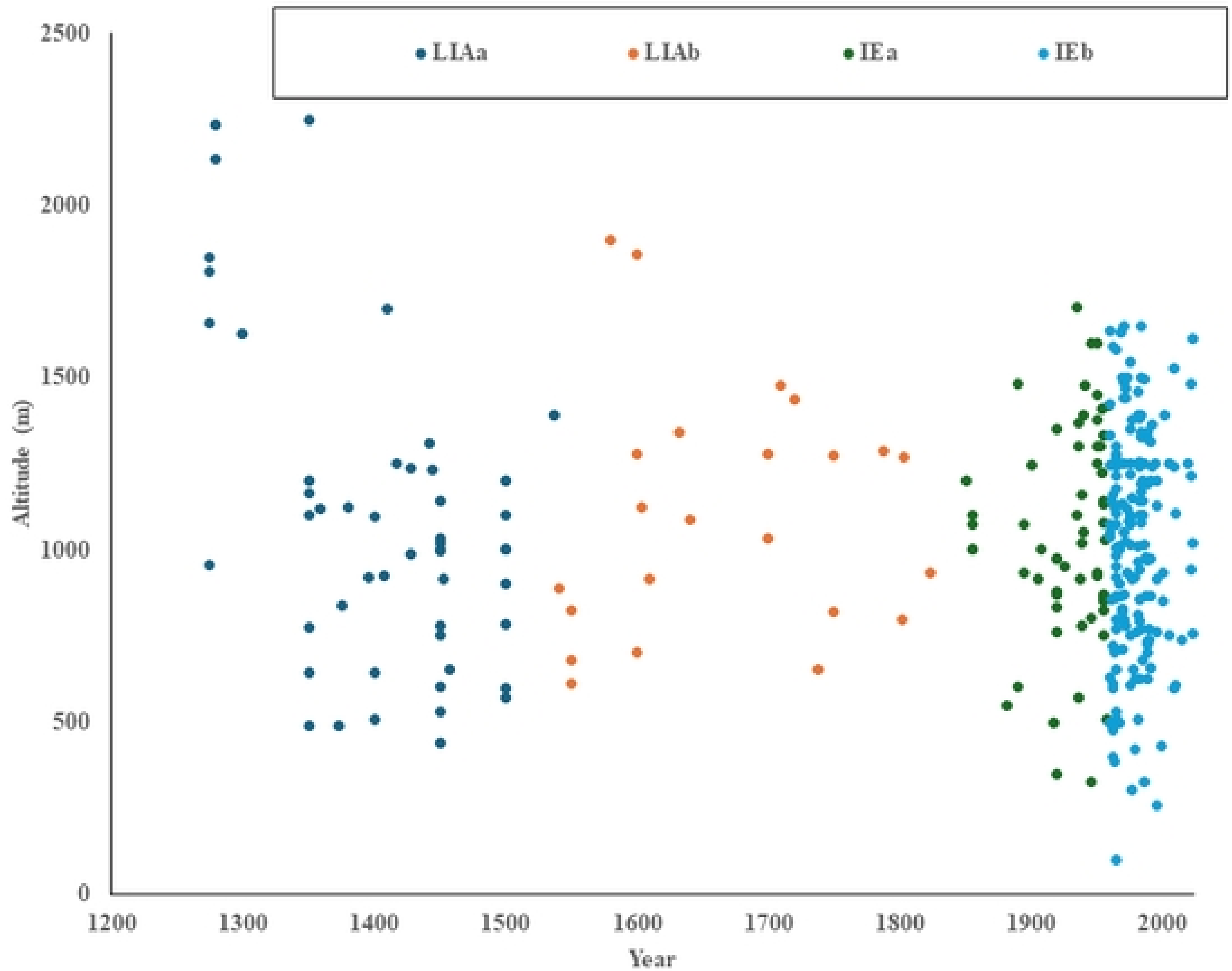

LIAa
LIAb
IEa
IEb
2500
2000
1500
1000
500
0
Altitude (m)
1200
1300
1400
1500
1600
1700
1800
1900
2000
Year

Fig S1