Last millennium climate variability in the Romanian Carpathians: a synthesis

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ABSTRACT

The Carpathian Mountains span Central and Eastern Europe and provide vital ecosystem functions and services. For this reason, the conservation status of the Carpathians is critical due to environmental pressures such as deforestation and the impacts of climate change, which has significantly affected the region's ecosystem dynamics and communities through increased frequency of floods and landslides as well as changes in species distribution. Paleoclimatic proxy archives are essential to identifying climate trends. This paper aims to synthesize the climatic changes observed in the Romanian Carpathians in the last millennium, having paleoclimatic records as a base. During the Medieval Climate Anomaly (MCA) period in the Romanian Carpathians, wetter conditions prevailed mainly during the first part of this period, followed by a drying trend until the end of the MCA, while slightly warmer conditions were observed throughout the entire period. The timings were somewhat different between the northern and southern regions of the Romanian Carpathians. Another important climatic period, the Little Ice Age (LIA), was characterized by highly variable climatic conditions linked to forcings such as volcanic eruptions and solar activity. LIA was generally dry with intermittent episodes of heavy rains. Winter temperatures dropped between AD 1500 and 1750, while currently available proxy records suggest that summer temperatures were slightly above average. The LIA reached its coldest point in the early 19th century. Since then, Romania has been experiencing warmer conditions, during the so-called Current Warm Period (CWP), with temperatures increasing significantly after 1970, leading to negative impacts on agriculture and hydrology. While positive precipitation anomalies were recorded in the 19th and early 20th centuries, a decline in precipitation has been widely observed since 1970, with an increased occurrence of extreme climatic events. The current warm period in Romania is part of a larger trend of global warming attributed to human activities, such as fossil fuel combustion, leading to environmental and socioeconomic impacts. These paleoclimatic observations provide context for current climatic trends and emphasize the need for joint efforts by governments, NGOs, and local communities to develop adaptation and mitigation strategies in order to reduce the potential negative impacts of climate change on Romania's environment and population.

Keywords: Carpathian Mountains; Romania; Climate change; Medieval Climate Anomaly; Little Ice Age; Current Warm Period.

INTRODUCTION

Paleoclimatology studies past climates and changes that have occurred over centuries, millennia, and longer geological timescales. This field of research seeks to understand the drivers of climate change, including natural factors such as volcanic activity and solar variability, as well as human-induced factors such as greenhouse gas emissions. Paleoclimatic studies utilize a variety of sources, also known as natural proxy archives, to reconstruct past climates, including ice cores, tree rings, sediment cores, and fossil records (Bradley, 2014). Overall, paleoclimatic studies are critical in advancing our understanding of the Earth's climate system and how it has changed over time (Cronin, 2009). By analyzing past climatic trends and patterns, scientists can develop models and scenarios that help predict how the Earth's climate will respond to future changes, which is essential for developing effective climate policies and strategies to mitigate potential impacts (Lenton et al., 2019).

The Carpathian Mountains are a vast mountain range spanning Central and Eastern Europe, covering over 200,000 square kilometers. The mountain range stretches across seven countries, including Romania, Ukraine, Poland, Slovakia, Hungary, Serbia, and Czechia, and is home to over 15 million people (Kruhlov et al., 2018; Werners et al., 2014). The Carpathians are a vital source of water, timber, and other natural resources for the region and provide important ecosystem services such as carbon sequestration and biodiversity conservation (Hlásny et al., 2016). The conservation status of the Carpathians is a critical issue for the region, as the area faces a range of environmental pressures and threats, including deforestation, pollution, and climate change impacts (Hlásny et al., 2016, 2017; Werners et al., 2014).

Climate change is one of the most pressing challenges facing the Carpathian Mountains, with changing precipitation patterns, rising temperatures and more frequent extreme weather events all significantly impacting the region's ecosystems and communities (Micu et al., 2015a). According to the Carpathian Convention (http://www.carpathianconvention.org/), the impacts of climate change on the Carpathians include increased frequency and severity of floods and landslides, changes in the distribution and abundance of animal and plant species, and changes in the quantity and quality of water resources. These impacts are not only environmental but also have significant social and economic consequences for the region, affecting agriculture, tourism, and human health. This global warming trend is attributed to increased greenhouse gas emissions from human activities, such as burning fossil fuels, deforestation, and industrial processes. This tendency has led to changes in the timing of natural events, the region's hydrology, and the distribution of plant species.

More than half of the world's population benefits from mountain ecosystems as they provide crucial resources such as water, energy, and agricultural products (FAO, 2016). However, high-elevation regions where the impact of climate change is amplified often lack adequate attention and resources for decision-making processes (Huss & Hock, 2018). This is largely due to their remote locations, inaccessibility, and lower economic status (Götsch et al., 2017). This review aims to compile and summarize the results of previous paleoclimatic studies conducted in the Romanian Carpathians, particularly during the last millennium, to be used as a source of information to support the region's conservation management strategies against potential impacts of future climate changes.

The Romanian Carpathians

The Carpathians, located between latitudes 50°N and 44°N and longitudes 17°E and 27°E, constitute the largest and longest portion of the European Alpine system, covering an area of 170,000 km^2 (Micu et al., 2015a). Figure 1 shows the elevation profile of the Romanian Carpathians and their position in Eastern Europe. The region is home to unique ecosystems, including forests and grasslands untouched by historical anthropogenic activities, that are rich in biodiversity and support a range of large carnivores such as wolves, bears, and lynx. These mountains also play a vital role in providing fresh water to three major rivers: the Danube, Dniester, and Vistula (Götsch et al., 2017). The region's temperate forests host pure and mixed elevation ecosystems (e.g., beech and beech/fir, respectively) between 950 and 1350 meters above sea level (a.s.l.) (Carpathian Ecoregion Initiative – http://www.carpathians.org/; Chivulescu et al., 2021).

More than 40% of the Carpathian surface is located within the territory of Romania, where local and regional climatic features are determined by the combined effects of latitude and longitude, topography, and regional atmospheric circulation (Micu et al., 2015c). While during winter the climate is influenced by the inflow of polar continental air masses from the east and northeast, in summer, oceanic air masses from the west predominate. The degree of continentality also varies throughout the Romanian Carpathians, with the highest located in its central portion, in the Transylvania region, and in the lower parts of the southern slopes (Götsch et al., 2017). The maximum temperature (T_{max}) ranges from 4.3 to 10.6 °C in areas above 800 m and from 11.6 to

17.1 °C in valleys, while the minimum temperature (T_{min}) varies more extensively throughout the region (Micu et al., 2015c). While T_{max} is known to respond to global radiation totals, T_{min} is site-dependent, with variations linked to cold air drainage and pooling capacities (Micu et al., 2015c). Total precipitation varies significantly due to complex interactions between topography, orographic, and regional flow dynamics. The mountain range is situated in an area where five major pressure systems intersect, including the Azores, the East-European and Scandinavian Anticyclones, and the Mediterranean and Icelandic Cyclones (Micu et al., 2015b). Climatic models suggest that positive (negative) anomalies of the North Atlantic Oscillation (NAO) and the East Atlantic/Western Russia pattern (EAWR) are linked to negative (positive) winter precipitation anomalies in the region (Monica Ionita, 2014; Warken et al., 2018). This intricate configuration, combined with the topographic and orographic effects on atmospheric flows, creates high inter-site variability, where detecting changes presents a genuine challenge.

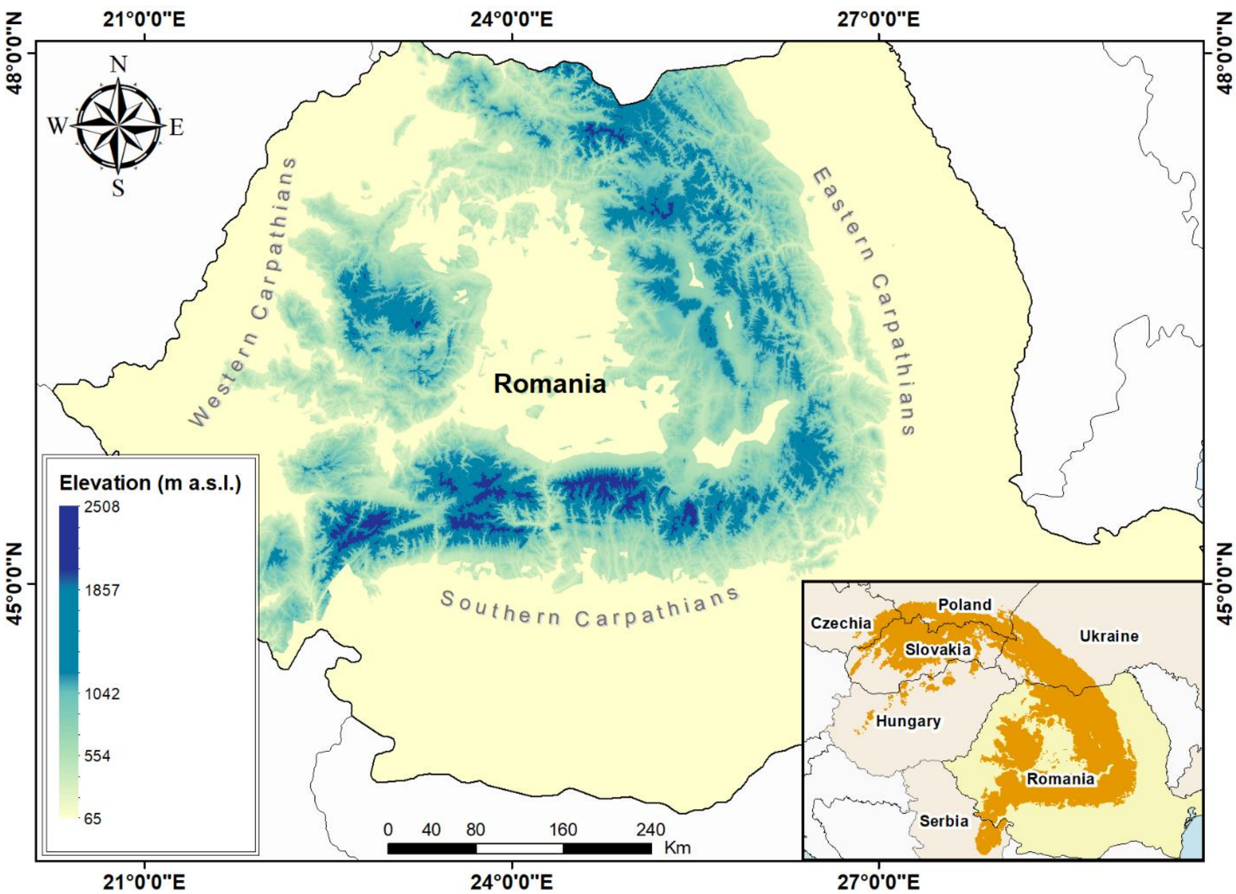

Figure 1 – Elevation profile of the Romanian Carpathians (main map) and the location of the Carpathian Mountains within Easter Europe (inset). Data for the elevation profile was obtained from SRTM Void filled dataset at the U.S. Geological Survey database (https://earthexplorer.usgs.gov/). Romanian Carpathians delineation based on European Mountain Areas dataset from the European Environment Agency (https://www.eea.europa.eu/en). Created using ArcMap 10.8.1 software.

The last millennium in the Romanian Carpathians

It is still a matter of debate whether the climatic dynamics observed in the present persisted in the past since incongruities in temporal trends can be observed among climatic reconstructions (Cleary et al., 2017; Constantin et al., 2007; Longman et al., 2017; Onac et al., 2002; Roberts et al., 2012; Warken et al., 2018). The past millennium's climate can be roughly divided into three intervals: the Medieval Climate Anomaly (MCA), also known as the 'Medieval Warm Period' (~AD 800–1300), the 'Little Ice Age' (LIA; ~AD 1500–1850; Mann et al., 2009), and recent warming during the past few decades, known as the Current Warm Period (CWP) (Mann et al., 2003).

Figure 2 represents a spatiotemporal summary of the climatic changes observed in the proxies cited in this review. The figure highlights the climatic trends of the records and the inferred climatic driver relative to the current long-term average. During the first part of the MCA (AD 917 ± 95 – 1204 ± 83), a similar response was observed among the natural archives in the Eastern and Southern Romanian Carpathians, generally reflecting wetter conditions. Conversely, records from the Western Romanian Carpathian suggest drier and warmer conditions. For the LIA (AD 1370 – 1880), all records agree on the prevalence of drier and colder conditions throughout the entirety of the Romanian Carpathian. While records indicate warmer but wetter conditions during the first part of the CWP (AD 1900 – 1970), the second part of the CWP (AD 1970 – Present) clearly reflects a warm and dry scenario.

In the following sections, we will use the existing paleoclimatic studies from Romanian Carpathians to describe these climate changes observed over the three climatic intervals in more detail.

Medieval Climate Anomaly (MCA)

The Medieval Climate Anomaly (MCA) was a period of generally warm conditions in the Northern Hemisphere that occurred between ~AD 800 – 1300, with a peak between AD 950 – 1100 as evidenced by proxy-based temperature reconstructions (Christiansen & Ljungqvist, 2012). It has been observed that the magnitude of temperature anomalies varied significantly across different regions, and some records show greater variability in temperature over time compared to others.

Moreover, records from different regions may not agree regarding the synchronicity, trend, or magnitude of temperature shifts over time, as reported by Büntgen et al. (2006), Christiansen & Ljungqvist (2012), and Lionello (2012).

In the Romanian Carpathians, the MCA was characterized by fluctuations in precipitation and temperature. According to Feurdean et al. (2015), the MCA period in Romania was considerably wetter than today, as indicated by testate amoeba-inferred water table depth from an ombrotrophic peat profile in the Rodna Mountains (northern Romania) between AD 800 – 1150. However, the authors observed dry mire conditions after AD ~1150 until the end of the MCA.

Cristea et al. (2014) reported a rise in $\delta^{13}C$ levels in bulk peat within the Maramureș Mountains (northern Romania) from the onset of the MCA until AD ~1245 and interpreted it as a result of wetter conditions, which was followed by drier conditions in the following decades. A high-resolution speleothem trace element record from Cloșani Cave, southwestern Romania, indicated that more humid conditions were observed for the region only between ca. AD 900 and 1200, while conditions became drier and similar to modern conditions for the remainder of the MCA until AD 1430 (Warken et al., 2018). The same drier trend was observed in other natural archives in Southern Romania, for example, in the total minerogenic matter from Sureanu peat (Longman et al., 2017). A decrease in terrigenous influx, related to low erosion and indicated by the Titanium record from Lake Ighiel, Northwest of the Carpathians, was observed during almost the entire MCA, especially between AD 950 – 1250 (Haliuc et al., 2017). Guano deposit analysis in Gaura cu Muscă cave, located in southwest Romania, indicated wet conditions between AD 990 – 1090. However, except for a brief period around AD 1170, drier conditions prevailed until the end of the MCA in this location (Onac et al., 2014). The same pattern was observed in the $\delta^{13}C$ record from Urșilor Cave, NW Romania (Onac et al., 2002). Warken et al. (2018) suggested that a persistent positive NAO phase during the late MCA may have contributed to the drying trend observed in Romania. Still, the authors noted that the impact of this phenomenon was not as evident during this period compared to other parts of the record.

Nonetheless, Feurdean et al. (2015) suggested that the moist conditions observed during most of the MCA could be attributed to the impact of maritime air masses in the region. They also noted that despite the prevalence of wetter conditions, the absence of a decline in summer temperatures (Landrum et al., 2013; Popa & Kern, 2009) made it unlikely that increased Atlantic influence was responsible for this phenomenon, as this would have resulted in lower surface temperatures. Therefore, the authors proposed that a greater influence from other major moisture sources, such as the Black Sea, or other phenomena such as delayed snow melt, likely caused the wet conditions observed in their proxy. In contrast, deuterium-excess values analyzed in cave ice point to the Atlantic Ocean as the main source for the wetter conditions observed for the region (Perșoiu & Perșoiu, 2019). Still, the authors also pointed out that a northward penetration of Mediterranean cyclones must have occurred due to the prevalence of an NAO positive phase, leading to generally wet conditions. Clearly, this issue is an ongoing debate, and further research is still needed to understand better the relationship between these processes and the relative contributions of various moisture sources for the Romanian Carpathians during the MCA.

Regarding temperature, $\delta^{18}O$ values from Poleva Cave suggested warm climate conditions during the MCA in SW Romania (Constantin et al., 2007). Equally, the presence of bats in the Măgurici Cave (NW Romania) between AD 1049 – 1298, indicated by a radiocarbon-dated bat guano deposit, was associated with a warmer climate (Johnston et al., 2010). A slight positive shift in $\delta^{18}O$ values around AD 950 in a peatland from Valea Morii, NW Romania, was also interpreted as a result of a warmer climate (Gałka et al., 2018). However, a tree ring-based July temperature reconstruction from the Călimani Mountains (N Romania) suggests no evident warming in the region between AD 1000 – 1300 (Popa & Kern, 2009). This observation is in line with global atmosphere simulations, which indicate that, although the region experienced warmer winters during the MCA, summer temperatures did appear significantly higher compared to the present (Landrum et al., 2013).

In summary, the MCA in Romania was characterized by wetter conditions prevailing mainly during the first part of this period (AD ~800 – 1200), with a subsequent drying trend that persisted until the end of the MCA and the onset of the LIA, displaying slightly different timings between the northern and southern regions of the Romanian Carpathians. Reduced snow cover and relatively even precipitation distribution throughout the seasons have also been inferred from available records (Perșoiu & Perșoiu, 2019). In general, however, temperature reconstructions showed that slightly warmer conditions during the entire MCA were more characteristic for the winter than summer.

Little Ice Age (LIA)

The Little Ice Age (LIA) was a period of widespread global cooling that occurred between the 14th and 19th centuries, with most records showing the coldest conditions between AD 1580 and 1880 (PAGES 2k Consortium, 2013). While it is difficult to determine the exact timing of LIA extent in Romania, available records from the region suggest that the timing of the LIA likely occurred between AD 1370 and 1630 based on a record from the Călimani Mountains in the Eastern Carpathians (Popa & Kern, 2009), or between AD 1400-1690 as indicated by another record in the Apuseni Mountains, Western Carpathians (Feurdean et al., 2011; Geantă et al., 2012; Perşoiu & Pazdur, 2011).

In Romania, the onset of the LIA was generally characterized by a continuation of the drying trend that started in the second half of the MCA. Low growth rates and high Mg/Ca ratios from a stalagmite in southwestern Romania indicate a peak in dry conditions between 1675 and 1715 (Warken et al., 2018). The authors highlighted that no direct connection between this trend and NAO variability was visible in their records. Evidence of a dry LIA was also recorded in a peat bog profile from the Eastern Carpathians between AD 1550 and 1750 (Feurdean et al., 2015). A pattern of reduced precipitation was also observed in the pollen record from NW Romania (Feurdean et al., 2008). A lacustrine record from Lake Ighiel (Western Carpathians) displayed low variability in their proxy record between AD 1250 and 1700 related to low levels of erosional activity linked with generally dry conditions (Haliuc et al., 2017).

The dryer conditions in Romania during the LIA contrast with wetter conditions observed for NW Europe, indicating a complex regional pattern (Feurdean et al., 2015). In general, eastern Europe showed a weaker LIA temperature drop, probably linked to the enhanced influence of continental air masses caused by changes in atmospheric circulation and resulting in a moisture gradient declining from the NW towards the SE (Feurdean et al., 2015; Haliuc et al., 2017; Longman et al., 2019). Although central and eastern European palaeohydrological records generally offer a contradictory account of LIA conditions, peat geochemistry analysis in the Southern Carpathians showed a clear correlation between local records and flooding/precipitation records from the Alpine region, with notable occurrences of sporadic bouts of heavy rainfalls (Longman et al., 2019), also suggested by macrofossils preserved in cave ice (Feurdean et al., 2011). Perșoiu and Perșoiu (2019) also observed the indication of flash floods probably associated with heavy summer thunderstorms. They also suggested that these wet conditions arose from a combination of increased local storminess and moisture transport from the North Atlantic in combination with the southernly position of the westerlies related to the negative phase of the NAO.

Tree ring records from the Northern Carpathians suggest cold conditions between AD 1370 and 1630 and between AD 1820 and 1840, separated by somewhat warm summers, particularly between AD 1640 and 1740 (Popa and Kern, 2009). The authors also identified the longest cold epoch in the last millennium, which lasted from 1430s to the 1630s. Tree ring parameters indicated generally cool summers and milder conditions centered around AD 1490 and 1545 (Popa and Kern, 2009). The cold periods recorded around AD 1300 and 1450 in their data are associated with the Wolf and Spörer Minima, respectively (Popa & Kern, 2009; Stuiver & Braziunas, 1989). The researchers also highlighted close agreement with large-scale reconstructions between 1750 – 1850, associated with the combined effect of the Dalton Minimum and two significant volcanic eruptions (Tambora in 1815 and an unknown eruption in 1809; Dai et al., 1991; Oppenheimer, 2003). These findings were also supported by a multiproxy reconstruction from the northern Romanian Carpathians (Haliuc et al., 2016).

Interestingly, the Călimani reconstruction strongly correlates with Alpine reconstructions between AD 1460 and 1510, probably indicating a dominant regional forcing in the eastern Carpathians and the Alps, resulting in a distinct European signal rather than a global one (Popa and Kern, 2009). It is also worth noting that the temperature decrease magnitude was smaller than both the worldwide mean and the European reconstruction cited in the Büntgen et al. (2011) and Christiansen and Ljungqvist (2012) studies (Feurdean et al., 2015). The absence of bats in Măgurici Cave (NW Romania) between ca. AD 1300 and 1647 was interpreted as the result of colder temperatures linked with the onset of the LIA (Johnston et al., 2010) and is in line with tree-ring-based reconstructions for the region (Popa and Kern, 2009). A lack of deposition in bat guano was also observed in both NW and SW Romania caves linked to dryer conditions around AD 1670, which changed to a wetter trend towards the end of the LIA (AD 1790 – 1900; Cleary et al., 2018, 2019).

In summary, the LIA was characterized by highly variable climate conditions, with temperature and precipitation patterns differing over time. The cooling during the LIA was likely caused by a combination of factors, including volcanic eruptions, solar activity, and atmospheric dynamics linked to ocean circulation patterns. Between AD 1500 and 1750, winter temperatures dropped while summer temperatures were slightly higher than average (Perșoiu and Perșoiu, 2019). In contrast, the coldest point of the LIA (considering both summer and winter conditions) occurred at the beginning of the 19th century (Perșoiu and Perșoiu, 2019). Regarding precipitation, the LIA was generally dry but with intermittent episodes of heavy rains observed in a wide range of proxies. From the onset of the LIA until 1450s, climatic conditions were variable, with cooling and drying tendencies, the occurrence of Mediterranean cyclones, and substantial snow cover in the mountains (Perșoiu and Perșoiu, 2019). The driest period of the millennium occurred between AD 1550 and 1750, with cold winters and slightly warmer-than-average summers leading to increased seasonality.

Current Warm Period (CWP)

Romania is currently experiencing a warm period that began after 1820 – 1850 and has continued into the 21st century. This warming trend is present in both summer and winter temperature records, both proxy-based and instrumental climatic datasets from meteorological stations. Warken et al. (2018) analyzed the precipitation anomalies in NW and SW Romania during various periods throughout history. The researchers found that positive precipitation anomalies in both NW and SW Romania characterized the 19th century and the period between AD 1900 and 1925. Relatively dry periods were recorded during the years AD 1926 – 1936. The decline in the stalagmite growth rate during the AD 1970s co-occurred with a substantial decrease in the guano $\delta^{15}N$ record, corresponding to a significant reduction in precipitation. The authors interpreted this shift as a possible association with a change from negative to positive phases of both the NAO and the EAWR, as previously also mentioned by other researchers (Cleary et al., 2017). However, the study found no clear correlation between Cloșani (SW Romania) precipitation anomalies nor any distinct NAO phases for other prominent intervals. Per Longman et al. (2017), a periodically weakened influence of the NAO in the southern Carpathians was observed, suggesting strong regional forcing of hydroclimate in the Romanian Carpathians and a non-persistent relationship to the NAO, especially on (multi-)annual to decadal timescales.

Moist conditions and increased humidity, observed in the ombrotrophic bog profile from the Eastern Carpathians between AD 1680 – 1950, have been followed by the subsequent dry conditions and intensification in disturbance events such as forest clearance, fire, and peat drainage (Diaconu et al., 2020). According to Feurdean et al. (2015), mire surface conditions in the Rodna Mountains have dried significantly in the last 40 years, approaching the driest conditions seen over the past 1000 years. The drying trend was particularly pronounced from 1990 to 2010 (Dragotă and Kucsicsa, 2011).

In the CWP, extreme temperature indices exhibit a warming signal, with autumn being the only stable season concerning changes in temperature extremes. The long-term variability of daily precipitation extreme has been rather stable, with no significant trends observed at most stations. This inconsistency of changes in precipitation extremes leads to the conclusion that the decreasing trends in snow-related indices, especially the maximum snowfall spells, are related to recent warming (Ionita et al., 2020; Spinoni et al., 2015). Levanič et al. (2013) concluded that the number of extreme events was variable over time, and although the frequency occurrence of these events in the 20th century was similar to the 18th century, a considerable increase has been observed recently. Climate prediction models indicate that the southern and eastern parts of Romania are the most vulnerable regions to drought (Barbu & Popa, 2004 *apud* Cleary et al., 2019).

According to a study by Dragotă & Kucsicsa (2011), the Northern Romanian Carpathians have experienced a rise of 0.7°C in the mean annual air temperature and a reduction of 100 mm in annual precipitation over the past two decades, particularly since 1980. This warming tendency was also observed in a tree ring-derived reconstruction from the Eastern Carpathians, where an abrupt increase in temperature, with an unprecedented amplitude at a millennial scale identified after 1980. Between the end of the LIA and the late 20th century, the summer temperature record shows a slight non-continuous warming trend (Popa and Kern, 2009). Micu et al. (2015) found that the growing season length (GSL) has not been considerably affected despite rising mean annual temperatures. However, other studies have noted the opposite, with the temperature increase leading to a longer GSL, which positively and negatively impacts agricultural productivity. While some crops have benefited from the longer growing season, others have been negatively impacted by increased heat stress and water shortages (Hatfield & Prueger, 2015; Nelson et al., 2009; Zhao et al., 2017).

The current warm period has significantly affected Romania's natural forest ecosystem processes. Shifts to another ecosystem's climate have been observed in many forest species' climate envelopes (Mihai et al., 2022). Moreover, the warming trend has caused some plant species to expand their range while others have contracted (García-Duro et al., 2021). Simulations indicate that changes in species composition can be followed by a notable decrease in aboveground live carbon storage

(Kruhlov et al., 2018). Observations, however, indicate different responses of forest landscapes to climate change. Biomass production has generally increased over recent decades in response to the prolonged growing season and rising temperatures across the northern and southern Romanian high-altitude forests (Schurman et al., 2019). However, tree growth sensitivity to temperature has decreased over the same period, as the climatic constraints to tree growth are transitioning from temperature to moisture limitation with declining altitude and latitude (Babst et al., 2013, 2019). These results highlight the need for region-specific forest management and conservation strategies (Chivulescu et al., 2021), as the future impacts of global environmental changes in the Romanian Carpathians will likely be tied to non-climatic gradients dictating future ecosystem responses.

According to Zaharia et al. (2020), warmer temperatures have affected Romania's hydrology: since 1960, there has been a general decrease in mean annual streamflow. During winter, an increased water flux has been observed, reflecting higher rates of liquid precipitations at the expense of snowfall due to increased air temperature. Contrarily to this trend, during the summer, the increase in evaporation due to a general warming trend has caused a decrease in discharge, and model simulations suggest that this pattern is expected to be exacerbated in the future (Zaharia et al., 2020). Romania's agriculture and energy production sectors are at risk due to the decreased water supply caused by shifting climatic pressures. The seasonal variability in precipitation induced by climate warming strongly affects crop yield in Romania's most important agricultural areas, the south and southeastern regions (Prăvălie et al., 2017). Extreme weather events such as droughts and floods have become more frequent, reducing crop yields and increasing crop losses (ClimateADAPT, 2023 – https://climate-adapt.eea.europa.eu/en/countries-regions/countries/romania).

The current warm period in Romania is not an isolated event but rather a part of a larger global warming trend. According to the Intergovernmental Panel on Climate Change, average global air temperatures have risen by 0.85°C since the late 19th century, with most of the warming occurring in the past few decades, which could non-linearly increase risks for human and natural ecosystems if current warming transiently exceeds 1.5°C in the coming decades (IPCC, 2021)(IPCC, 2022). While some of these changes may have positive effects, such as the "greening effect" and extension of the upper treeline, others could exacerbate current infrastructural and policy-related issues with significant consequences for Romania's agriculture, energy production, ecology and human health. The changes brought by the current warm period highlight the need for comprehensive up-to-date studies of the severity of these changes across environmental gradients, in order to promote adaptation and mitigation strategies that could alleviate potential negative impacts of climate change on Romania's ecosystem process and human landscape.

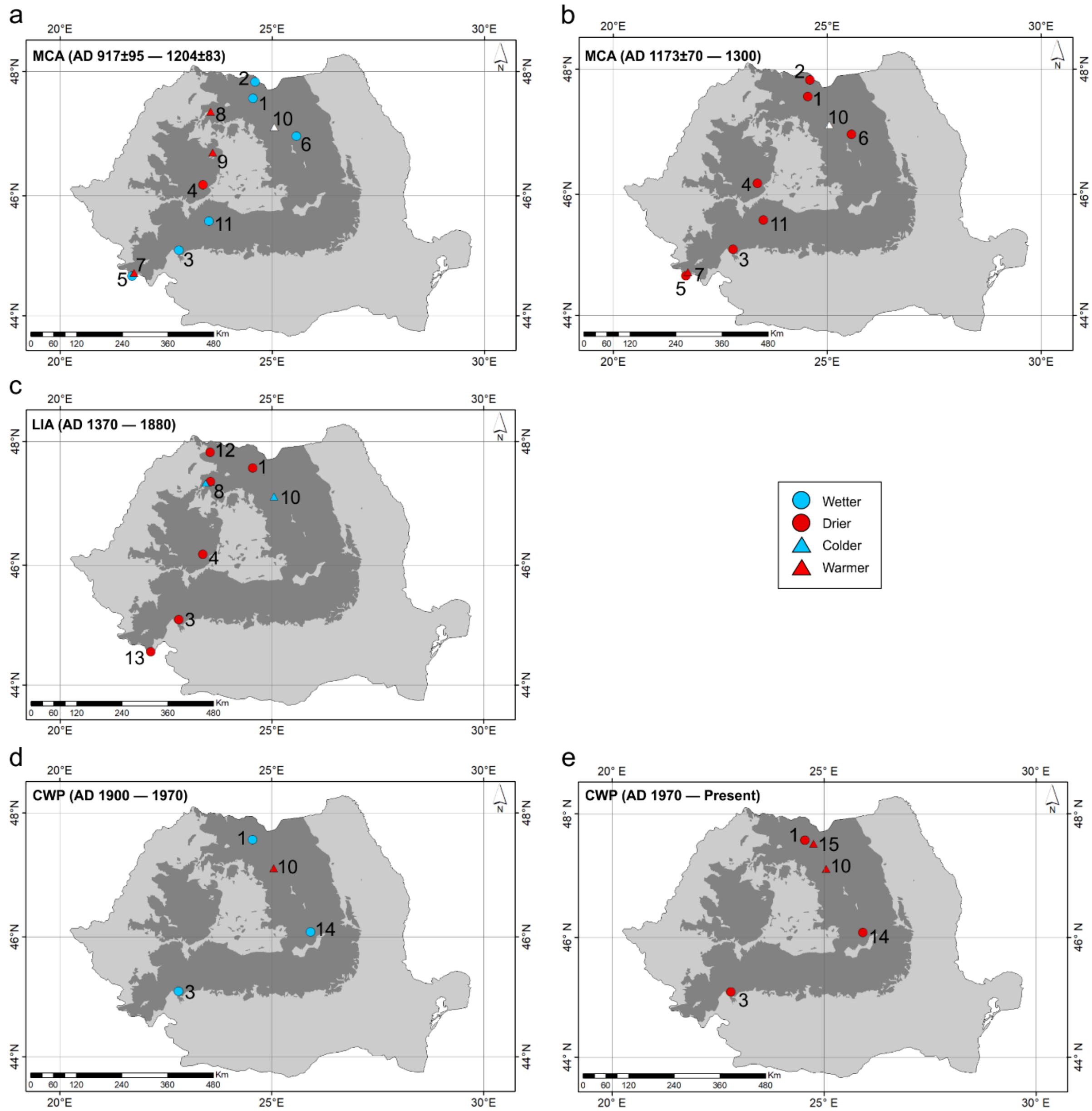

Figure 2 – Overview of the climatic interpretations for the Romanian Carpathians during the: a) early period of the Medieval Climate Anomaly – MCA (917±-95 – 1204±83); b) latter period of the MCA (1173±70 – 1300); c) Little Ice Age (1370 – 1880); d) early period of the Current Warm Period – CWP (1900 – 1970); and e) latter period of the CWP (1970 – Present). Circles represent precipitation proxies, with blue colors indicating wetter conditions and red indicating drier conditions. Triangles represent temperature proxies, where blue indicates colder conditions and red warmer conditions. Numbers refer to study site: 1 – Tăul Muced (Feurdean et al., 2015); 2 – Tăul Mare-Bardău (Cristea et al., 2014); 3 – Cloșani Cave (Warken et al., 2018); 4 – Lake Ighiel (Haliuc et al., 2017); 5 – Gaura cu Musca (Onac et al., 2014); 6 – Urșilor Cave (Onac et al., 2002); 7 – Poleva Cave (Constantin et al., 2007); 8 – Măgurici Cave (Johnston et al., 2010); 9 – Valea Morii (Gałka et al., 2018); 10 – Călimani Mountains (Popa & Kern, 2009); 11 –

Sureanu peat (Longman et al., 2017); 12 – Preluca Tiganului (Feurdean et al., 2008); 13 – Gura Ponicovei (Cleary et al., 2019); 14 – Ciomadul Massif (Diaconu et al., 2020); 15 – Iezer weather station (Dragotă and Kucsicsa, 2011). Created using ArcMap 10.8.1 and CorelDRAW 2018 softwares.

The importance of paleoclimatic studies linked to environmental management in the context of future climate change

In the context of current and future climate change, paleoclimatic studies are essential for informing environmental policymakers and conservation managers. Past climate and environmental reconstructions provide a long-term perspective on the Earth's climate system and insight into the natural variability of the climate system and the mechanisms that drive changes in climate and the environment. Thus, Paleoclimatic studies play a crucial role in developing a more detailed understanding of past climatic conditions and predicting the most likely scenarios of future climate change more accurately. With increasing concern over global warming's impact on natural environmental processes comes the need for accurate and reliable data to inform environmental management strategies.

As we are dealing with an indirect way to reconstruct the past climate, it is worth mentioning that there are some uncertainties associated with proxy-based reconstructions. One major issue is the spatial and temporal representativeness of the proxy records, which may not accurately reflect regional or global climate patterns, and therefore the importance of moving the focus toward finer-scale, denser networks of regional reconstructions. Additionally, multiple environmental factors, such as changes in land use or nutrient availability, may influence proxies, which can complicate or limit their interpretation. Moreover, proxy records may contain measurement errors or gaps, leading to uncertainties in reconstructing past climate variables, besides potential errors derived from statistical data treatment. Therefore, while climatic reconstructions based on proxies can provide valuable information about past climate variability, it is essential to consider these uncertainties when interpreting the results. Hence, increasing the number and spatial resolution of paleoclimatic proxy records and reconstructions is crucial while reducing uncertainty by improving their quality (St. George & Esper, 2019).

In the context of the Romanian Carpathians, paleoclimatic studies are of particular importance due to the significant role these mountains play in the region's water cycle, ecology, and agriculture. The Romanian Carpathians have a complex and dynamic climate shaped by several factors, including topography, latitude, and the interaction of oceanic and continental air masses. These mountains are an essential water source for the region, providing water to several rivers that supply water for irrigation and hydroelectric power generation. The region's ecology and agriculture are also highly dependent on the mountains' climatic conditions. Climate change is expected to significantly impact the region's water resources, ecology, and agriculture, making it crucial to understand past climatic conditions and their impact on the region's environment.

Insights gained from paleoclimatic studies can directly assist in developing environmental management strategies and policies. For example, in the Romanian Carpathians, paleoclimatic studies can help predict future changes in the region's water resources, ecology, and agriculture and inform strategies to mitigate these changes. One example is the development of adaptive agriculture practices that can cope with changing precipitation patterns and increased temperatures. Similarly, the information gained from paleoclimatic studies can inform water management policies and strategies, ensuring the region's water resources are sustainably managed.

Various conservation organizations, such as the Carpathia Foundation (https://www.carpathia.org/) and World Wildlife Fund (WWF; https://wwf.panda.org/), have taken the initiative to address the detrimental effects of climate change in the Carpathian region. These organizations have devised a range of programs aimed at enhancing the resilience of ecosystems and communities in the region while promoting sustainable development and biodiversity conservation. These programs include promoting sustainable land use practices like agroforestry and sustainable forestry management, developing renewable energy sources, and creating green corridors to facilitate the movement of plant and animal species in response to changing environmental conditions. Additionally, the Carpathian Convention has developed a few programs, such as the Carpathian Climate Change Adaptation Framework and the Carpathian Network of Protected Areas, to tackle the impacts of climate change in the region.

Despite these efforts, the Romanian Carpathians still face significant challenges related to implementing rural policies and management practices that will conserve valuable resources, mitigate the impacts of extreme weather events, and reduce agricultural land and infrastructural fragmentation (Chiper, 2015; Halbac-Cotoara-Zamfir & Halbac-Cotoara-Zamfir, 2018; Micu et al., 2022). To achieve this, coordinated efforts from governments, NGOs, and local communities are necessary, as well as investment in research, education, and raising awareness to build resilience and promote sustainable development. Collaborative efforts could position the Carpathian region as a leader in climate change adaptation and mitigation, inspiring other mountain regions worldwide facing similar challenges.

CONCLUSIONS

The significance of climate change on a global scale cannot be over- or understated given its societal, economic, and political impacts, as highlighted by the (IPCC, 2022). Consequently, it is crucial to understand the current state of the climate system within the framework of past climatic variability while also acknowledging that instrumental climatic records rarely cover more than a couple of centuries. That is where paleoclimatic proxy archives play an important role in inferring climatic trends in earlier periods. Although traditionally there has been significant interest in large-scale hemispheric reconstructions of climatic variability, there is a growing emphasis on developing more detailed and denser networks of regional reconstructions, in particular the ones with lower associated uncertainty, as ultimately, this is important to gain a better and more accurate representation of past climatic variability. Enhancing the spatial resolution of reconstructions is imperative to obtain a more precise understanding of past climate variability at the local and regional levels. This will also diminish dependence on a limited number of records and allow for better comparison and validation among reconstructions, which is still an issue in the relatively underrepresented Romanian Carpathians. An important aspect is developing a more comprehensive understanding of local and regional fluctuations in the duration and intensity of warmer and colder periods during the past millennium.

There is still a scarcity of high-resolution studies that analyze climatic/environmental conditions over the past millennium when anthropogenic activity has been a consistent factor. Some questions, such as the spatiotemporal patterns of climate change across the Carpathians and regional responses to large-scale atmospheric patterns, remain a matter of debate and require further research, especially with an emphasis on temporally long, high-resolution, locally-calibrated reconstructions.

From this review, it is clear that there has been an overall increase in temperatures and the occurrence of extreme hydrological events such as drought and floods in the Romanian Carpathians, especially since 1980. The Carpathian Convention has recognized multiple priority areas for conservation, including the protection of biodiversity, sustainable management of natural resources, and promotion of eco-tourism and sustainable development. However, despite these conservation measures, it is critically important for governments, NGOs, and local communities to continue working together to safeguard this vital region for future generations.

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