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STEĆCI TOMBSTONES: LIMESTONE MONUMENTS IN DIFFERENT CLIMATE ZONES

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Abstract

Stećci, medieval tombstones from the 12th to 16th centuries, are found primarily in present-day Bosnia and Herzegovina and its bordering regions of Croatia, Serbia, and Montenegro, distinguished by intricate carvings and inscriptions. This paper describes ten necropolises—Blidinje, Ravanjska Vrata, Radimlja, Križevići, Kopošići, stećci at the National Museum of Bosnia and Herzegovina, Cista Velika, stećci at the Museum of Croatian Archaeological Monuments in Split, Mramorje, and Žugića Bare-along with archaeological work and documentation at these sites. The study examines the impact of climate change on the preservation of stećci. By characterizing thermo-pluviometric parameters and classifying the sites within the Köppen climate system, the research highlights regional climate variations affecting stone deterioration. The analysis reveals that most necropolises are located in climate classes C and D, including types Cfa, Cfb, Csa, and Dfb. Over the past 30 years, increased sunshine, higher temperatures, and radiation have been observed, along with significant variations in humidity and precipitation and a decrease in snow cover. GIS-based mapping shows spatial trends in vulnerability, offering insights to guide future conservation strategies. By integrating archaeology, climatology, and geospatial analysis, this study emphasizes the need for adaptive conservation to protect stećci as vital cultural heritage.

***Keywords**: Stećci; Limestone; Archaeology; Climate change; Köppen climate classification; Limestone deterioration*

Introduction

Climate change, manifested as extreme weather events and growing levels of environmental pollution, poses a real risk to cultural assets, particularly limestone structures. Limestone, which is mostly made of calcium carbonate, is especially sensitive to chemical weathering. As a tangible remnant of our common global culture, it is critical to devise comprehensive ways to prevent or reduce the consequences of climate change on these irreplaceable monuments. But what is the "extreme" value? According to the literature, an occurrence is considered extreme if the value of a variable exceeds (or sits below) a threshold [1]. The thresholds are defined in a variety of ways, leading to differing views of what constitutes an extraordinary occurrence. Because of the nature of this report, two definitions of extreme events are discussed. Firstly, extreme values are defined as those exceeding a relative threshold, typically set at a high percentile (≥ 90%) within each time series. For example, given an annual maximum

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daily value time series (e.g., annual maximum daily rainfall, annual maximum daily temperature), any value greater than the relative threshold would be termed exceptional.

Second, extreme values might be defined as those values that surpass an absolute threshold. Following the preceding example, for a given magnitude, extreme events relate to annual maximum daily values that surpass a threshold value, independent of time series. The line between non-extreme and extreme events is usually defined by the implications that these extreme values may cause (e.g., health impacts, irreversible damage to goods, biodiversity loss).

The intensifying impacts of climate change, especially extreme rainfalls, floods, and landslides, pose a grave threat to our stone heritage structures, including stećak tombstones. These climatic changes can drastically deteriorate these sacred limestone monuments, causing them to lose their original integrity or to disappear completely. Given the nature of their composition, these limestone structures are particularly vulnerable to the adverse physical and chemical reactions invoked by intense rainfalls. Moreover, the recent report by the Intergovernmental Panel on Climate Change [2] indicates that rainfall extremes and consequent soil saturation are expected to increase in frequency due to climate change. This can lead to increased landslides and flooding, which can erode and even displace the limestone tombstones and other equally sensitive stone structures.

One of the foundational resources in this field is the paper by Orr *et al.* 2021 [3]. The authors systematically reviewed 165 publications released from 2016 to 2020 to assess what advancements had been made in the field. One of the key findings of the study was the continued growth and disciplinary diversity of this research field. However, they also noted that there had been a predominance of research set in Europe and a relative lack of international collaboration in this field. The authors found an increase in research around integrating cultural heritage into processes of climate change adaptation and mitigation, but these still constituted only a small fraction compared to research about the physical impacts on individual buildings or sites. Moreover, they observed that research has hardly ever examined the effects of climate change on intangible cultural heritage, encompassing traditions, customs, expertise, and knowledge. As stated by the writers, research must be situated within more comprehensive frameworks in order to comprehend the associated potential and challenges. They underscored the necessity for enhanced global collaboration and the exchange of knowledge to safeguard cultural heritage against the adverse effects of climate change.

Stećci tombstones

The extensive limestone formations throughout the Balkans have played a crucial role in shaping both the natural landscape and cultural heritage, particularly in the construction of stećci, medieval tombstones found in Bosnia and Herzegovina, Montenegro, Croatia, and Serbia. These limestone-rich regions, including the Dinaric Alps and other karst-dominated terrains, provided an abundant and easily workable source of stone for sculpting these distinctive monuments.

Limestone used for stećci reveals a predominant composition of calcite ($CaCO_3$), with textures ranging from fine-grained micritic to coarser sparitic structures. The presence of fossil inclusions, such as benthic foraminifera and mollusks, indicates the ancient marine environments in which these stones were originally deposited. The specific lithological characteristics of the limestone influenced the durability and susceptibility of stećci to weathering processes, including dissolution, fracturing, and biological colonization.

The karst landscapes in which stećci are often found are marked by sinkholes, caves, and underground drainage systems, which influence local hydrology and microclimatic conditions. These factors, in turn, affect the conservation of stećci, as karst terrains are particularly prone to moisture fluctuations, acid rain exposure, and biological growth such as lichens and mosses. Over centuries, these environmental conditions have contributed to surface discoloration, erosion, and structural degradation of the tombstones.

Understanding the geology and petrography of the limestone used in stećci is essential for their preservation. Targeted conservation strategies must consider the stone's mineralogical composition, porosity, and exposure to atmospheric pollutants, particularly sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which accelerate chemical weathering. By integrating geological studies with conservation efforts, it is possible to develop effective protection measures that mitigate environmental impacts and ensure the long-term survival of these significant cultural monuments.

Stećci are medieval limestone gravestones that date back to the 12th-16th centuries and are found across the Western Balkans. Primarily found in Bosnia and Herzegovina (B&H), they are also present in smaller numbers across Croatia, Montenegro, and Serbia, regions bordering B&H. These tombstones generally come in six distinct forms, with more than 72,000 still remaining in their original locations. They feature inscriptions in the Bosnian Cyrillic script (known as 'bosančica'), as well as reliefs that blend both European and unique regional artistic traditions [4], [5].

The burial tradition of stećci is typically understood in three parts: their origins and historical context, the symbolism and artistic elements, and their spatial distribution and burial practices. These cultural practices played a crucial role in preserving the stećci, leading to Bosnia and Herzegovina possessing the largest collection of late medieval tombstones in Europe-and perhaps the world [6].

As shown in Figure 1, stećci come in six primary forms: slabs, chests, gables, crosses, columns, and irregular shapes. Chest-shaped stećci are the most prevalent. Gabled stećci, often richly decorated with carvings and inscriptions, are considered the most artistically refined, representing the peak of medieval Bosnian funerary art. While stećak production declined after the Ottoman arrival, their artistic legacy continues to influence aspects of modern culture [4], [7].

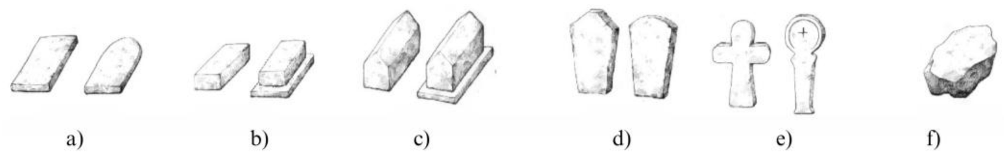


Fig. 1. Typical stećci forms: slabs, chests, gables, crosses, columns, and irregular shapes

Only around 6,000 stećci are decorated, with some examples being truly remarkable, such as the stećak from Zgošća near Kakanj, which exemplifies the pinnacle of medieval stonemasonry. Although there is a wide array of ornamental motifs, few researchers have attempted to categorize them, aside from some dubious scientific and pseudo-scientific classifications. The work of Marian Wenzel, a British art historian, remains the first and most comprehensive typology of stećci decorations. She categorized these motifs (Fig. 2) into several groups: geometric, architectural, and plant motifs (including lilies, bunches of grapes, vines, branches, and trees); animal motifs (featuring birds, deer, horses, dogs, fish, snakes, and other creatures); human motifs (such as hands, heads, half-figures, mounted figures, and individual and paired figures, as well as scenes of dancers in kolo and hunting); and simple decorative motifs (like crosses, recesses, sun circles, rosettes, crescents, and spirals) [8].

Inscriptions are even rarer than decorations, with fewer than 400 stećci monuments bearing them. This scarcity makes it difficult to accurately determine the chronological, cultural, or religious significance of these heritage items. The epitaphs are typically brief and written in *bosančica*. They usually contain basic details about the deceased and may sometimes include the names of the monument's creator, sculptor, and writer. Some inscriptions provide a short biography of the deceased, while others deliver moral or religious messages, reflecting on the fleeting nature of the world. Many inscriptions express sorrow over the death of a knight who faithfully served their master. A number of these inscriptions also hold historical and documentary value, as they mention prominent individuals or refer to significant events in which the deceased took part [6], [7], [9].

Fig. 2. Typical stećci forms: slabs, chests, gables, crosses, columns, and irregular shapes

Conservation aspect

Studying the conservation state of stećci is essential for ensuring the preservation of their historical, artistic, and cultural significance, as well as for developing effective conservation strategies to mitigate environmental and anthropogenic deterioration. As UNESCO World Heritage monuments, they provide insights into medieval Balkan traditions but face threats from weathering, pollution, and human activity. The effective preservation of stećci requires the application of scientific techniques, such as material analysis, environmental monitoring, and structural stabilization. The development of sustainable conservation strategies is made possible through interdisciplinary collaboration among archaeologists, conservation scientists, geologists, ecologists, and engineers. By integrating these efforts, stećci can be safeguarded, ensuring that their historical and cultural legacy is preserved for future generations. To address these challenges, the *Stone monument ensembles and the climate change impact* (STECCI) project integrates conservation, environmental science, social sciences, and digital technology to develop the *Preservation Guidelines* for limestone monuments under two climate scenarios. By combining multidisciplinary efforts with international cooperation, enhanced monitoring, and the integration of scientific results into climate adaptation frameworks, the STECCI project fosters sustainable heritage management.

The necropolises included in the project (Fig. 3) were chosen in such a way as to respect several factors, primarily selected according to different geographical and climatic zones, ranging from coastal areas to large plateaus like Blidinje and to mountainous regions of central and eastern Bosnia, such as Kopošići or Križevići. In this way, the influence of climatic factors on the degradation of limestone, the primary material of stećci, can be systematically evaluated.

Unlike previous stećci studies that focus primarily on their cultural significance, this research uniquely examines how different climate zones affect their preservation. By characterizing the climate of selected necropolises across Bosnia and Herzegovina, Serbia, Croatia, and Montenegro, and identifying key climate change threats, this study provides new insights into the environmental challenges facing these monuments. This novel perspective bridges stećci heritage conservation with climate science, offering a foundation for more effective, climate-adaptive preservation strategies. According to Orr et al. (2021) [3], out of the 165 publications, 110 included an author or authors from a single region, 39 included authors from two regions, and 15 included authors from three or more regions. Overall, 223 instances of international collaboration were noted, of which 62 (27%) were intercontinental collaborations. One hundred and seven (48%) of the total instances were entirely within European regions (either mono-regional or between European regions). Only two papers on this subject have been published from Serbia and two from Croatia, while none have been published from Montenegro or Bosnia and Herzegovina.

Fig. 3. Selected necropolises as demo-sites within the STECCI project

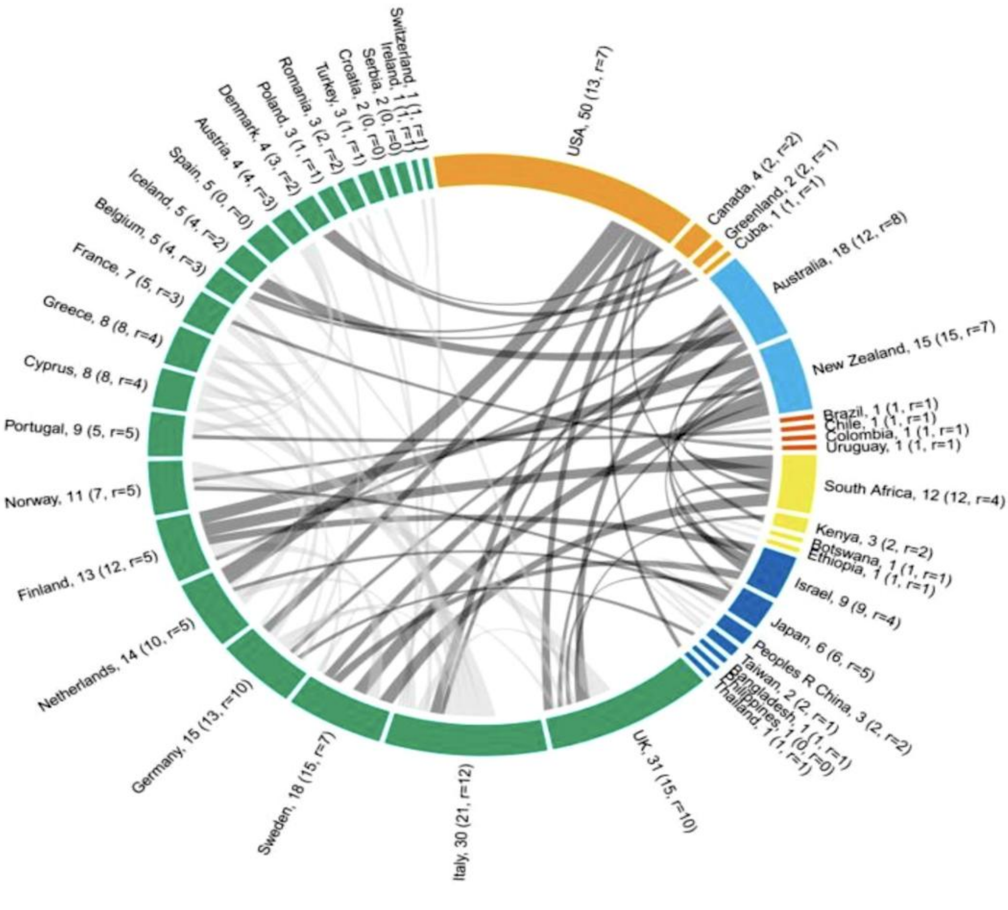


Fig. 4. Number of instances of authorship for publications on cultural heritage and climate change from 2016 to 2020, color-coded by continent. Darker links = intercontinental. Nomenclature: Country name, total publications (number of publications with international collaboration, r = number of regions). [3]

Experimental part

Fieldwork *and data collection*

Before the field survey of each of the selected necropolises within the STECCI project, a detailed review of all available literature and archival material was conducted to assess all activities at the sites in the past period. In the next phase, all necessary documentation and permits were collected to commence research work in the field. The fieldwork itself encompassed a detailed assessment of the condition of stećci at the sites of Radimlja, Dugo Polje, Kopošići, Ravanjska Vrata, and Križevići, the National Museum of B&H in Sarajevo (Bosnia and Herzegovina), Mala and Velika Crljivica in Cista Velika and the Museum of Croatian Archaeological Monuments in Split (Croatia), Mramorje in Perućac (Serbia); and the Žugića Bare in Žabljak (Montenegro) (respective geospatial positions provided in Table 1).

Table 1. Geospatial position of the investigated stećci necropolises

Necropolis name	Geospatial position and surface area
Dugo polje, **Blidinje**, B&H	φ = 43°39'47.85"N; λ = 17°32'35.46"E; H = 1,245 m; PNecr = 3,050 m^2
Ravanjska vrata, Kupres, B&H	φ = 43°51'48.68"N; λ = 17°18'44.44"E; H = 1,157 m; PNecr = 4,670 m^2
Radimlja, Stolac, B&H	φ = 43°05'31.52"N; λ = 17°55'26.22"E; H = 60 m; PNecr = 6,000 m^2
Križevići, Olovo, B&H	φ = 44°08'50.38"N; λ = 18°31'12.24"E; H = 610 m; PNecr = 5,080 m^2
Kopošići, Ilijaš, B&H	φ = 44°00'15.53"N; λ = 18°20'42.46"E; H = 966 m; PNecr = 215 m^2
National Museum of B&H, **Sarajevo**, B&H	φ = 43°51'18.98"N; λ = 18°24'11.37"E; H = 533 m; PNecr = 817 m^2
Velika Cista, HR	φ = 43°30'56.99"N; λ = 16°55'36.95"E; H = 478 m; PNecr = 2,900 m^2
Museum of Croatian archaeological monuments, **Split**, HR	φ = 43°57'27.87"N; λ = 19°25'49.28"E; H = 235 m; PNecr = 160 m^2
Perućac, Bajina Basta, SRB	φ = 43°57'27.87"N; λ = 19°25'49.28"E; H = 235 m; PNecr = 3.470 m^2
Žugića Bare, **Žabljak**, MNE	φ = 43°05'40.63"N; λ = 19°08'56.88"E; H = 478 m; PNecr = 820 m^2

Research on climate impacts and climate modelling

Before analyzing the climate types of the STECCI project necropolises, a literature review was conducted to identify existing knowledge gaps. Over 150 papers were reviewed to gain insights from previous studies, build on existing research, and address areas where understanding of climate change and conservation efforts is limited. The next phase involved practical research leading to the characterization of thermo-pluviometric parameters of broader areas of investigated project sites. For that purpose, data were collected from climate change agencies, STECCI requests for local information, and scientific sources. This was followed by creating a GIS database integrating diverse climate data into a single platform, enabling visualization of regional patterns, site-specific impact assessments, and temporal comparisons. Thus, the analysis evaluated climate change impacts on limestone monuments using ERA5-Land, ECAD gridded datasets, and meteorological data from stations near selected stećci sites. The mapping capabilities of the GIS system revealed spatial trends in vulnerability, guiding future conservation strategies for stećci. A 30-year climate dataset (1992–2022) was structured in Excel to include air temperature, precipitation, insolation, radiation, snow height, and extreme values. In some cases, due to limited on-site meteorological stations, data was interpolated from nearby stations using a linear regression model, linking climate elements with orographic features and air circulation. Official hydrometeorological data ensured accuracy and adaptability for digital database development. This methodology is the backbone of the STECCI project, and it is closely linked to developing the Preservation Guidelines - guidelines for monitoring and conservation of outdoor monuments made of compact limestones with respect to the changing climate, their setting, and exposure.

Communication with National Meteorological Stations has been crucial to understand how climate change is affecting each nominated STECCI site and what the most relevant impacts related to extreme events are (Table 2).

Table 2. STECCI monitoring sites

	Country	STECCI site	Meteorological station/source
1	BiH	Dugo polje, Radimlja, Sarajevo, Ravanjska vrata, Križevići, Kopošići	Sarajevo, Zenica, Mostar, Bugojno, Ivan Sedlo
2	HR	Velika Cista, Split	Station Sinj, Station Šestanovac DHMZ Croatian Meteorological and Hydrological Service
3	MNE	Žugića bare	Žabljak station *Source: Institute of Hydrometeorology and Seismology Montenegro* *HMS CG*
4	SRB	Perućac, Mramorje	Loznica, Bajina Bašta *Source: RHMZ* *Serbia Republic Hydrometeorological Service of Serbia*

Results and discussion

Sites descriptions

Over the last century and a half, since the systematic study of stećci began, there have been very few works that significantly addressed the examination of the impact of climatic factors on stećci. Conservation work has been carried out at certain sites, specifically at Radimlja near Stolac, Dugo Polje near Jablanica, Crljivica in Cista Provo, and Mramorje in Perućac. Furthermore, the works conducted in the past period mainly focused on descriptive analysis and descriptions of stećci, relating to the typological determination of the shapes of stećci, iconographic or stylistic analyses of decorations, reading and linguistic analysis of inscriptions where present at a specific location, as well as determining their historical, cultural, or religious context. Archaeological excavations of graves beneath certain stećaks at sites such as Radimlja, Kopošići, Ravanjska vrata, and Mramorje (Perućac) have also revealed interesting details about the life and death of medieval people in this area, viewed through the lens of different social strata in society. At Radimlja, 11 graves were excavated. Most of them had a stone construction, and none contained grave goods apart from skeletons [10], [11]. At Ravanjska vrata, one grave was excavated beneath a tombstone in the lower necropolis. Below, the skeleton of a child was found without any grave goods [12]. At the necropolis of Mramorje, a total of nine graves were excavated. They were simple earthen graves covered with wooden planks. Two coins were discovered in the graves-one belonging to Despot Đurađ Branković and the other to the Bosnian king Stjepan Tomaš [13]. At the site of Velika and Mala Crljivica in Cista Provo, during 2004 and 2005, protective archaeological excavations were conducted on graves beneath several stećak tombstones during construction works carried out on and near the site. Some of the graves had stone-lined pits, while others were simple earthen graves. Grave goods were found in several graves, consisting of a few Venetian coins, pendants, or other small metal objects [14]. In 2015, archaeological excavations were conducted beneath seven stećak tombstones at the necropolis in Kopošići near Ilijaš. Some of the graves had already been plundered earlier, but the most significant discovery came from a grave belonging to the great Bosnian duke Mirko Radojević or possibly his grandson. The discovery consists of the remnants of a brocade cloak, where the textile threads were wrapped in a metallic sheath made of silver with gilding [5].

Blidinje is a stunning natural region in northern Herzegovina, featuring a prominent karst plateau located between the Čvrsnica, Muharica, and Vran mountains. At its center is Dugo polje, the area designated as a nature park, which spans several municipalities in Bosnia and Herzegovina. Dugo polje is home to Blidinje Lake, the largest mountain lake in the country, fed by melting snow from the surrounding peaks. Historically, Blidinje has served as a crossroads for trade routes between Bosnia and Dalmatia. The region exhibits traces of prehistoric graves and Roman roads, alongside medieval necropolises. Although it was largely uninhabited during harsh winter months, mobile pastoral communities established seasonal camps, or katuns, here as spring arrived [15]. The Dugo polje necropolis is the largest in Blidinje, boasting an area of untouched natural beauty and rich biodiversity. It comprises 150 preserved stećci (medieval tombstones), making it one of the larger necropolises in the region. The most common shapes are slabs, with 72 recorded, followed by 59 chests, 14 tall chests, and five gabled roofs, four of which have plinths. Notably, 32 stećci are decorated, including five slabs and all gabled roofs, yet none have epitaphs, which is unusual given their evident aesthetic value [16]. Crafted from local limestone, the stećci exhibit exceptional workmanship, with gabled roofs and chests being carved with more detail than the slabs. Several graves bordered by stone blocks are also present, and the stećci are arranged in regular rows, predominantly oriented southwest to northeast. This arrangement helps date the necropolis to the 14th and early 15th centuries, with the most exquisite monuments likely crafted in the first half of the 15th century. The necropolis is well-preserved, having undergone recent cleaning and conservation efforts. Its historical and cultural significance has led to its inclusion in the UNESCO World Heritage list, recognized for its exceptional craftsmanship and the authenticity of its expression [5].

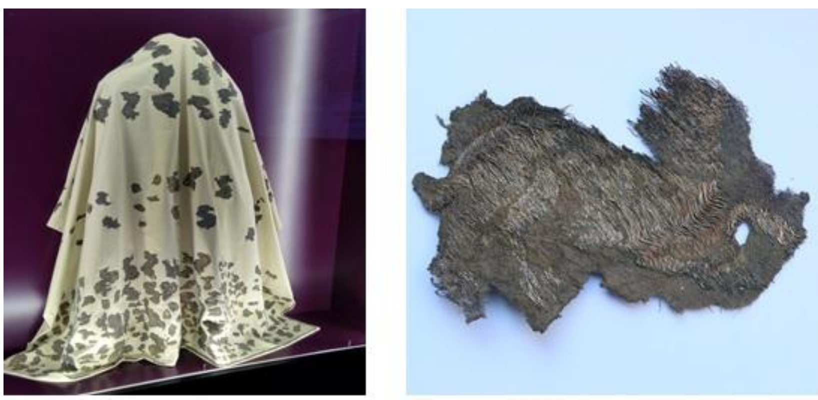
Kupres, located in western Bosnia, encompasses four high karst fields—Kuprеško, Rilićko, Ravanjsko, and Vukovsko—and is surrounded by mountains. Named after its administrative center, the region has evidence of past settlements despite its harsh living conditions. It is the most representative area for stećci (medieval tombstones) in western Bosnia, with over 1,000 spread across more than 40 necropolises, primarily consisting of slabs and chests, while gabled roofs are rare. The **Ravanjska vrata** necropolis stands out, located in a passage connecting Vukovsko and Ravanjsko fields. The area, historically significant for its prehistoric settlements and later roads, was used for livestock grazing. The necropolis is divided into two parts: the lower and upper necropolises. The Lower necropolis features 43 stećci, including 20 slabs, 20 chests, and three gabled roofs, with 18 decorated monuments. Just 50 meters away, the Upper Necropolis contains 25 stećci, with 15 decorated, showcasing motifs like rosettes, crescents, and stylized lilies [12], [16]. These stećci near the village of Mušići are a UNESCO World Heritage Site, though they lack epitaphs, leaving the identities of the deceased and their craftsmen unknown. The necropolis is disrupted by a local dirt road, reflecting the ongoing struggles of preserving these cultural treasures.

Radimlja is a notable necropolis located in Vidovo polje, just three kilometers west of Stolac, along the main road to Čapljina. Visitors to the area are immediately struck by the presence of 133 tombstones (stećci), although this number is believed to be lower than it once was due to damage from the road's construction during the Austro-Hungarian era, which likely resulted in the loss of about 20 stones. This development divided the necropolis, with some stećci remaining on one side of the road and others buried beneath it. Archaeological excavations led by Alojz Benac in the late 1940s uncovered evidence of plundered graves beneath some significant stećci [10].

Radimlja is renowned as one of the most decorated necropolises in Bosnia and Herzegovina, featuring an impressive array of ornamental motifs on its 63 decorated monuments. A distinctive emblem of the site is the depiction of a male figure with an exaggerated raised right hand, interpreted as a warrior pose, often accompanied by symbols like a bow, arrow, sword, or shield. Some scenes include a circular representation that might symbolize the full moon, which has been linked to pagan beliefs associated with the afterlife or even to the figure of Saint Vitus, supported by local historical references [17]. The stećci at Radimlja also showcase diverse figurative representations, including round dances involving men, women, and mixed groups, as well as depictions of animals such as deer, dogs, and horses. Scenes illustrate dogs herding deer toward a hunter ready with a bow, emphasizing the rich symbolism inherent in these images [10]. Five epitaphs inscribed in Bosnian Cyrillic provide insights into the individuals buried in the necropolis and suggest it may have originally been known as Batonoge. The necropolis is generally dated to the 15th century, reflecting the historical significance of this community [18]. Radimlja has been included in the UNESCO World Heritage list, highlighting its extraordinary artistic and historical value.

In the village of **Križevići**, near the municipality of Olovo, at the Gradina site, there is a necropolis of 42 stećci. Originally, there were more monuments, but many were taken for building materials during the construction of a bridge in 1914. Today, the necropolis includes six slabs, six chests, 29 gabled roof stećci, and one double gabled roof stećak, all made of limestone. Ten are decorated, showcasing motifs like spirals, rosettes, and horsemen, but none contain epitaphs. Notable monuments include a rare double-gabled roof stećak for two persons and the most decorated stećak at the site — a tall gabled roof with a plinth, featuring intricate designs on all sides. This tall stećak, tapering towards the bottom and adorned with twisted ribbons and rosettes, stands nearly 2.5 meters long. It exemplifies the craftsmanship of a stone-carving workshop from the late Middle Ages [16], [19], [20]. The necropolis is situated on Gradina Hill, likely the site of a prehistoric settlement.

Kopošići is a village near Ilijaš, central Bosnia, and home to a significant necropolis featuring stećci tombstones. The central area of the necropolis, located on a small hill next to a modern Catholic cemetery, contains nine stećci, while about 30 more monuments extend down the slope.



a) b)

Fig. 5. a) Fragments of archaeological textile found at the Kopošići necropolis near Ilijaš, which could be the burial shroud of Prince Mirko Radojević; b) Heraldic motive on the textile cloak.

The necropolis dates to the late 14^{th} and early 15^{th} centuries. Also, archaeological excavations conducted in 2015 revealed a surprisingly well-preserved brocade cloak made of silk interwoven with gilded silver threads in a grave that could be connected to great Bosnian prince Mirko Radojević or his grandson. However, the stećci in Kopošići are now endangered due to cracks, necessitating urgent conservation efforts to preserve these historical monuments [16], [21], [22].

Another location with stećci that has been studied as part of the STECCI project is the group of stećci currently located in the National Museum of Bosnia and Herzegovina in Sarajevo. This collection consists of 37 stećci (21 in the botanical garden, 10 in front of the museum, 2 in the medieval exhibition, and 4 in the ethnology department of the museum) that have been transferred from various locations in Bosnia and Herzegovina. These are representative specimens of richly decorated stećci, which in a certain way represent the complete region of stećak distribution, as well as their other most significant characteristics [23]. Extracted from their original environment, they are under significant anthropogenic influences, primarily from various pollutants, as well as the impacts of climate and weather conditions in Sarajevo. For this reason, these monuments were selected as one of the references for studying the aforementioned influences on the durability of limestone in an urban environment such as Sarajevo.

Cista Velika, in Croatia, is historically significant for its prehistoric and medieval cultural monuments, particularly the necropolis with stećci (medieval tombstones). The Crljivica site, featuring around 90 decorated tombstones, reflects continuous settlement and diverse cultural influences from prehistoric times through the Ottoman period. The necropolis is located along the main road Trilj–Imotski, stretching about 300 meters. It is divided into two groups, Velika and Mala Crljivica, forming a single unit. Despite damage from modern infrastructure projects, key artifacts and structures from the medieval period have been preserved and studied, highlighting the area's rich historical heritage. Notably, the Crljivica necropolis is one of two stećci sites in Croatia on the UNESCO World Heritage List. Today, around 90 stećci are preserved in the necropolis, with about half of them decorated. The repertoire of ornamental motifs includes various forms of crosses, crescents, stars, semicircular arcades, vegetal motifs, stylized lilies, and geometric decorations. Figural representations range from individual depictions to entire scenes of knightly tournaments, hunts, and dances. Two notable monuments with Cyrillic script inscriptions belong to Vladna and Herak Kustražić. Protective archaeological research in 2004 revealed several graves, with finds such as Venetian silver coins from the 14th century [14], [24].

Mramorje Bajina Bašta is a municipality in western Serbia, near the Drina River and the Bosnia and Herzegovina border. It has a continuous settlement history spanning seven thousand years. The nearby settlement of Perućac is known for its artificial lake and the largest necropolis with stećci (medieval tombstones) in Serbia, located at Mramorje or Bagruša.

Originally, around 200 stećci made of hard limestone were recorded here in the late 19th century. By the mid-20th century, this number reduced to 112, and the latest records indicate a further decrease to 93 stećci. Archaeological excavations in 2010 revealed 16 grave pits with skeletons of different ages and genders. Among the finds were coins from Serbian despot Đurađ Branković and Bosnian king Stjepan Tomaš, dating the necropolis to the 15th century. The necropolis has been cleaned and conserved for visitors. There are 30 additional sites with stećci in the Bajina Bašta area, and a modern cemetery nearby serves as evidence of the long continuity of burials in this region [16], [25], [26].

Žugića Bare is a small village located about 7 km southeast of Žabljak, on the plateau of Mount Durmitor. Near the village road, there is a necropolis with almost 300 stećci (medieval tombstones), one of the largest in the region, also known as the Greek Cemetery. The necropolis features various uncarved or roughly carved monuments, including 10 gabled tombstones, 50 chests, and 10 slabs. There are also graves marked with unprocessed stones. Of the total, 23 monuments are decorated with motifs such as crosses, round dances, and hunting scenes. Notably, one chest features a round dance with a rider on a deer, and that is a rare motif on stećci. The necropolis falls within the territory of the people (better known as 'tribe') of Drobnjaci, mentioned in documents from 1285. The necropolis in Žugića Bare can be roughly dated to the 14th and 15th centuries. Due to their size and preservation, three necropolises in present-day Montenegro are included on the UNESCO World Heritage list [27], [28].

Table 3. Key climate elements of selected STECCI necropolises

	Blidinje	Ravanjska vrata	Radimlja	Kopošići	Križevići	Sarajevo	Cista Velika	Split	Mramorje	Zugica bare
Av. monthly insolation (1992-2022) (h)	153.6	147.5	203	133	152.1	159.5	204.2	219.2	173.8	168.4
Increase of sunshine over the period (h)	46	227	33.6	156	229	200	-17	-15	122	278.6
Av. monthly radiation (1992-2022) (kWh/m^2)	103.8	100.0	137.0	90.0	103.6	107.4	138.0	147.7	115.4	113.0
Increase of radiation over the period (kWh/m^2)	38	141.6	23	98	150	129	-14	-12	77	116 **
Av. monthly temperature (1992-2022) (°C)	6.9	7.0	15.7	8.4	10.1	10.7	13.5	15.3	12.3	6.1 **
Increase of temperature over the period (°C)	1.3	1.7	1.3	1.6	1.5	1.5	1.3	1.7	1.8	0.04 **
Increase in maximum annual air temperature over the period (°C)	2.0	1.3	1.5	2.4	2.4	2.4	-0.3	-0.4	0.1	-1.1 **
Av.value of extreme minimum temperature (°C)	-10.1	-6.0	-4.3	-9.5	-7.9	-7.2	-5.5	-4.3	**-13.6**	-1.9 **
Av. relative humidity (1992-2022) (%)	78.2	79.6	62.3	76.3	74.6	69.8	63.4	65.3	74.1	76.4 **
Relative humidity trend over the period (%)	2.1	1.7	8.2	-2.8	-2.5	-2.3	-1.9	-2.0	2.3	3.7 **
Av. annual precipitation (1992-2022) (mm)	129.6	94.2	119.4	92.0	81.7	78.17	113.0	118.9	73.6	128.8
Precipitation trend over the period (mm)	83.2	36.4	90.0	-54	-46	-45	-6.6	92	**49.6**	59
Long-term average precipitation (mm)	1555.2	1130.7	1433	1103.8	980	938	1350.7	1426.8	1242.4	1555.0
Av. monthly snowfall (2015-2022) (cm)	**13.9**	5.6	*	7.4	6.3	6.2	*	*	6.8	31.9
Snow cover trend over the period 2015-2022 (cm)	-48.2	-22.6	*	-33.4	-27	-26.8	*	*	-0.7	-113 **

* there were almost no snowfalls recorded during the 30 years period
** over the period between 2000 - 2022

Climatic Characteristics of Europe and Project Necropolises

Europe's climate is shaped by physico-geographical position, geomorphology, land-sea distribution, atmospheric circulation, and ocean currents. Its triangular shape allows maritime air to penetrate inland via the Atlantic and North Sea, while the Mediterranean moderates African tropical influences. The Ural Mountains and rivers link Europe to Asia, amplifying climatic contrasts. With a highly indented 37200 km coastline (4.1 km per 1000 km²), regional climate variation is further influenced by large islands, peninsulas, and inland seas like the Mediterranean and Baltic, which modify air masses through hydro-thermal effects. This paper synthesizes the continent's climatic diversity, focusing on the broader spatial zones of designated necropolises (Table 1), and highlights the methodologies and findings of the STECCI project.

Table 3 shows that over the past 30 years, most sites have experienced an increase in sunshine duration, correlating with higher air temperatures across all climatological seasons and radiation. There are significant monthly variations in relative humidity and precipitation; some areas show increasing precipitation trends in spring/winter, while others experience declines in summer/autumn. Snowfall is highest in January or February, but snow cover depth is generally decreasing. There are also some site-specific trends, such as a more pronounced decrease in maximum annual temperatures in Žabljak and no recorded snowfall in Radimlja, Split, and Cista Velika. An example of annual trends of thermal and pluviometric regimes for some of the sites in Bosnia and Herzegovina and sites in Serbia and Montenegro is provided in Figs. 6A and B.

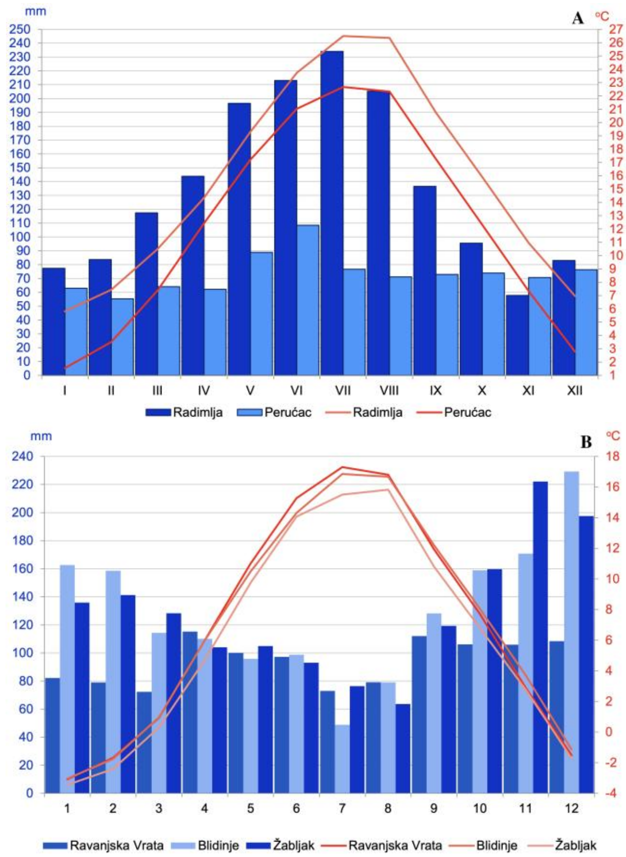


Fig. 6. Annual Trends of Thermal and Pluviometric Regime in Climatic Subtype Cfax in the following sites: **A**) Radimlja and Mramorje, Perućac; **B**) Ravanjska vrata, Žabljak, Blidinje.

Evidence indicates that climate change, reflected in temperature fluctuations, shifting precipitation patterns, rising sea levels, and more intense storms, hurricanes, and landslides, combined with urbanization, presents substantial risks to cultural heritage [29]. The Köppen Climate Classification is crucial for conservation science, as it helps predict environmental stressors affecting cultural heritage based on climate zones. Different climates pose distinct risks, such as biological growth in humid areas, salt weathering in arid regions, and freeze-thaw damage in temperate and polar zones. Without prompt conservation and adaptation efforts, these threats could result in deformation, deterioration, or even the complete loss of cultural heritage sites. The classification also aids in climate modelling, allowing researchers to forecast deterioration risks and develop site-specific preservation plans. By providing a standardized framework, it supports international cooperation and climate-resilient heritage conservation efforts. Figure 7 shows the Köppen Climate Classification for the whole of Europe, whereas figure 8 is specific to the selected project sites.

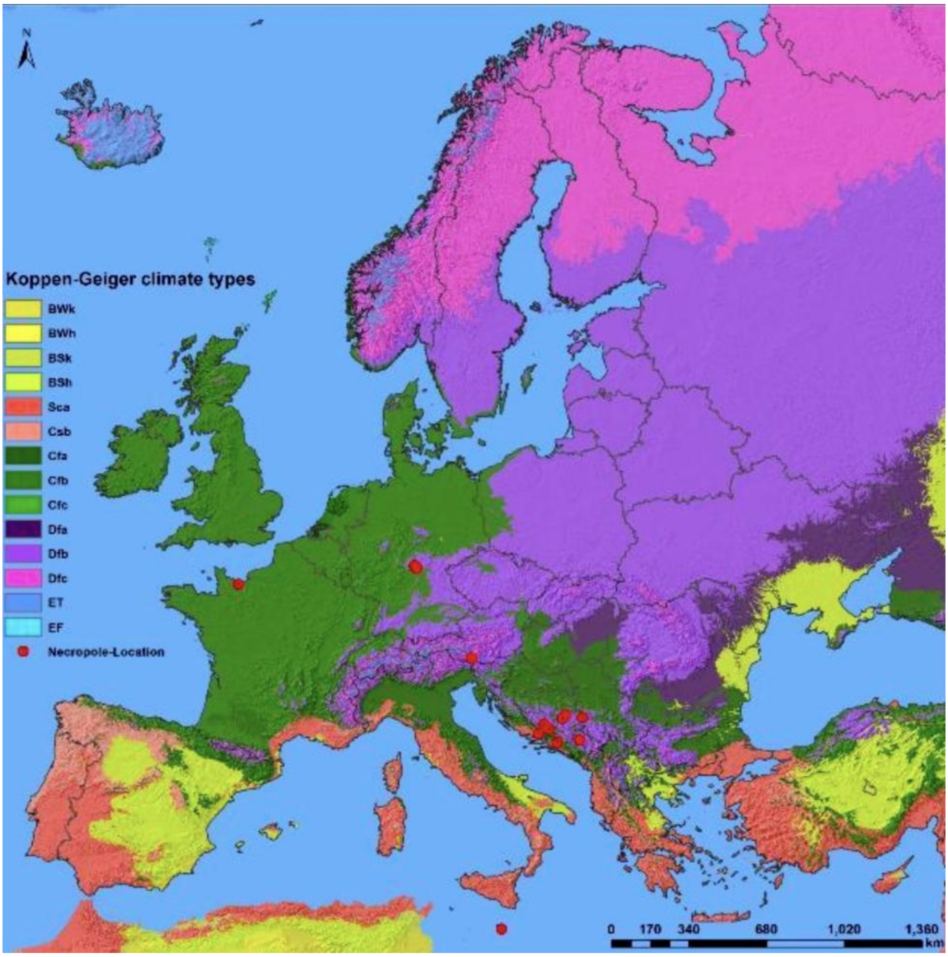


Fig. 7. Geographical Distribution of Main Climatic Types According to the W. Köppen Climate Classification in the European Region *(Author: N. Drešković, S. Radulović)*

Based on thermal and pluviometric trends, the investigated sites fall into two Köppen climate classes: C and D, as presented in Figure 8. Class C, found in lowlands up to around 1000 m, has warmest-month temperatures above 10°C and coldest-month temperatures above -3°C, with annual averages ranging from 8 to 16°C. Precipitation exceeds 1000 mm, with maritime-influenced areas experiencing wetter winters and drier summers. This class includes the Cf type, characterized by year-round precipitation, and the Cs type, found in the Mediterranean region, with dry summers and most precipitation occurring in colder months. Class D, present above 800 m, has similar summer temperatures but colder winters below -3°C, with annual temperatures ranging from 2 to 8°C. Precipitation varies between 700 and 3000 mm and follows the Df type, marked by evenly distributed rainfall throughout the year.

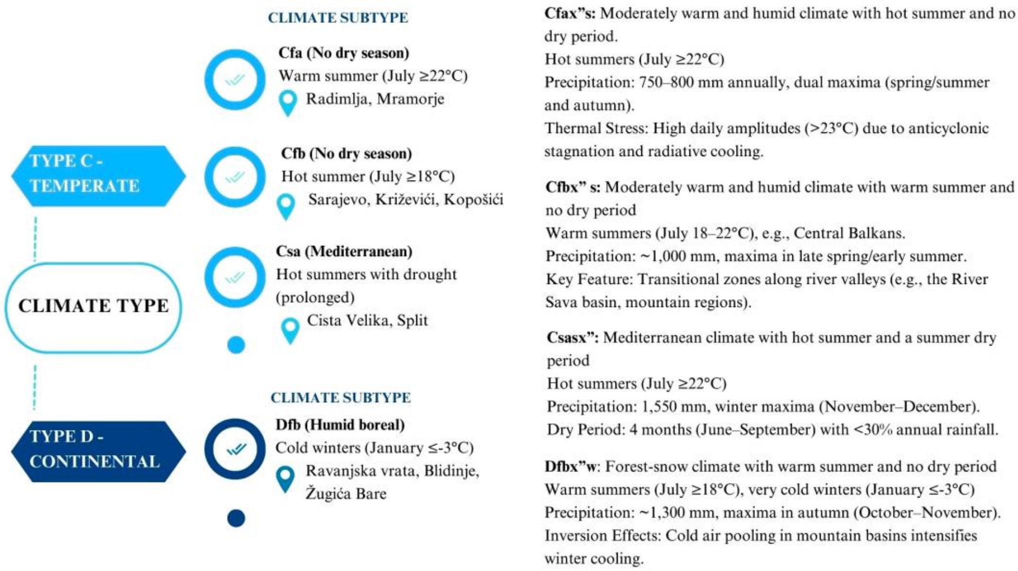


Fig. 8. Climate types, subtypes, and variants in the investigated sites according to Köppen's classification.

Climate change and stone monuments

Steiger *et al.* [30] provides crucial insights into the possible devastation that climate change could inflict upon limestone structures, in addition to offering substantial clarification regarding the appropriate usage of terminology. The authors define deterioration is a complex process, and therefore, there are many words that are used to describe it. As an illustration, the term "weathering" refers to the inherent process by which external elements deteriorate rocks, whereas "deterioration" denotes the degradation of their utility and worth. Thus, stones degrade while rocks undergo weathering. The distinction is that the stones were produced and utilized by humans. These two words are therefore not synonymous. On the other hand, "alteration" is defined as a modification of the material; for example, geologists use it to refer to the change in a mineral composition of a rock, such as occurs in volcanic rocks. The word does not imply a worsening of its characteristics from a conservation point of view [31], [32]. The aforementioned terms are commonly used interchangeably with two additional terms. These terms are "deterioration" and "degeneration." Both terms indicate a negative transformation, with the former signifying disintegration and carrying particular significance for chemists, physicists, and geologists. By translating it as "biodegradation," biologists effectively avoided any potential misunderstandings. In contrast, decay is synonymous with decomposition or rotting, as seen by the presence of decay in teeth. A few years ago, an online dictionary included an additional definition of "decay" as "the consequence of being neglected and destroyed." This is an aspect that should consistently be considered while contemplating the preservation of structures and landmarks. Finally, the last word that needs to be mentioned is damage. This is the most general term and needs to be accompanied by a qualifying term, as in "mechanical damage." There are many types of damage that stones can undergo [33]. It is important to point out that the same pattern may result from different deterioration mechanisms, while any one specific mechanism may result in different types of patterns, depending on the substrate in question.

In conclusion, climate change and its escalating ramifications, particularly intense precipitation, landslides, and flooding, can pose an extreme threat to limestone structures such as stećak tombstones. Knowledge of these risks is crucial in safeguarding this significant cultural heritage.

Extreme weather events such as storms, heavy precipitation, increased freeze-thaw cycles, and potential flooding, in the worst cases, can physically erode limestone monuments, eventually washing them away.

Our review of 165 papers from over 100 publication sources revealed a highly diverse body of literature on the intersection of cultural heritage and climate change (Fig. 9).

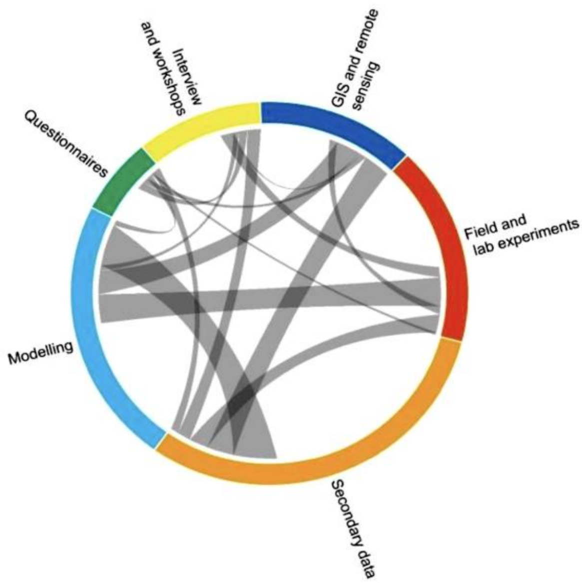


Fig. 9. Chord diagram illustrating research approaches in 165 cultural heritages and climate change studies (2016–2020), with linkage thickness indicating method co-occurrence [3]

In addition to that, it was established that research on climate impacts remains Eurocentric, focusing on physical degradation (e.g., salt crystallization, freeze-thaw cycles) rather than adaptation. Studies often rely on a single climate model, overlooking uncertainties. Climate models based on the Köppen Climate Classification predict significant warming in the region, shifting Csb (warm-summer Mediterranean) and Cfb (temperate oceanic) zones toward a Csa (hot-summer Mediterranean) climate. This temperature rise will impact ecosystems, agriculture, and water availability. Mediterranean regions (Csa/Csb) will face more frequent and severe droughts, heatwaves, and wildfires, while inland Dfa/Dfb (Hot-summer humid continental) Warm-summer humid continental zones may see increased heavy rainfall and flooding. Coastal areas, particularly along the eastern Adriatic, risk flooding due to rising sea levels. These climatic shifts threaten the Balkans' unique biodiversity, including many endemic species.

Weathering, erosion, and natural degradation of stećci vary significantly across different climatic regions due to distinct environmental stressors. Water remains the dominant agent of material decay across Europe, with precipitation, humidity, and temperature fluctuations accelerating corrosion, biological growth, and salt crystallization. Water exposure can degrade stone surfaces through expansion and contraction or freeze-thaw cycles, causing cracks, exfoliation, spalling, delamination, or contour descaling [34]. In Alpine regions, such as Blidinje in Bosnia and Herzegovina (1,245 m altitude), extreme freeze-thaw cycles and UV exposure lead to thermal stress, surface cracking, and progressive structural instability. Continental sites experience similar challenges, with severe seasonal temperature shifts intensifying both physical and chemical weathering. Mediterranean and Atlantic sites, on the other hand, face heightened risks of salt weathering and microbial colonization due to erratic rainfall and prolonged humidity. Salt crystallization from sea spray and groundwater evaporation weakens the stone matrix, while lichen, algae, and bacteria thrive in the humid conditions, accelerating surface deterioration. Lichens alone can colonize fresh stone and sandstone surfaces in both humid and dry conditions. Over time, other microorganisms follow, establishing and developing on these initial colonizers. Organic and inorganic acids (such as sulphuric and nitric) produced by colonizing biota are key biochemical agents that contribute to stone deterioration [35]. Urbanized areas, such as the National Museum of Bosnia and Herzegovina in Sarajevo, are particularly vulnerable to acid rain corrosion, where pollutants like sulfur dioxide and nitrogen oxides lower the pH of rainfall (<5), dissolving limestone surfaces over time. This is not only true for limestone but also other types of stone materials such as limestone, marble, concrete, and mortar [36]. The chemical dissolution and physical deterioration consequently lead to inscriptions and decorative carvings being eroded, thus making historical details increasingly illegible [37]. Wind-driven rain further compounds degradation across all regions, promoting surface abrasion and water infiltration, which weaken tombstone structures. As climate change intensifies, these processes are expected to accelerate, exacerbating erosion, biological colonization, and geospatial shifts. The tombstones, predominantly composed of limestone and dolomite, are especially susceptible to these environmental pressures, necessitating urgent conservation measures tailored to each climatic zone individually. These conservation measures will be developed in the following project stages as part of the *Preservation Guidelines* applicable to limestone monuments of similar characteristics in the whole of Europe. Although this paper is primarily focused on climate-related vulnerability assessment, conservation studies on carbonate stone highlight that the choice and safety of interventions depend strongly on stone microstructural heterogeneity and the presence of surface impurity layers-particularly relevant for laser cleaning due to potential thermal effects and micro-damage [38]. In addition, protective treatments can be evaluated through UV-accelerated aging to verify whether consolidation and water-repellent performance remain stable over time [39]. At a broader practice level, structured approaches for the conservation of façade artworks (40) and the development of eco-friendly materials for stone monument protection [41] provide sustainable options that can be aligned with priorities emerging from climate vulnerability assessments.

Conclusions

The phenomenon of stećci has been included on the UNESCO World Heritage List, thereby justifying their recognition as having cultural and historical significance on a global scale. Unfortunately, regardless of their historic, cultural, and artistic value, stećci today represent a heritage that is largely threatened by both anthropogenic factors and the impacts of climatic and weather conditions. Based on the comprehensive analyses, the selected necropolises were found to be located in the Köppen climate classes C and D, with the following types: Cfa, Cfb, Csa, and Dfb. Over the past 30 years, most sites have seen an increase in sunshine duration, linked to higher air temperatures across all seasons and radiation. Monthly variations in relative humidity and precipitation are significant and snow cover depth is generally decreasing. The obtained results showed that different climate zones present unique challenges and opportunities for conservation. The collaboration between archaeologists, conservators, climate scientists, and materials scientists is essential to address complex conservation challenges. The upcoming research in the STECCI project will develop Preservation Guidelines that consider the deterioration mechanisms and patterns of limestone monuments under various climate scenarios up to the year 2100 across Europe. This research will significantly contribute to inter- and transdisciplinary advancements in the field of cultural heritage preservation.

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