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Assessing Climate Impact on Heritage Buildings in Trentino—South Tyrol with High-Resolution Projections

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Abstract

Climate variations impact the preservation of heritage buildings, necessitating a strategic understanding of potential effects to effectively guide preservation efforts. This study analyzes temperature- and precipitation-dependent climate-heritage indices in Trentino–South Tyrol using EURO-CORDEX regional climate models for the period 1971–2100 under RCP 4.5 and RCP 8.5 scenarios. The selected indices were calculated with climdex-kit and relied on bias-adjusted temperature and precipitation data with a 1 km spatial resolution. The obtained results indicate a geographically punctuated increase in biomass accumulation on horizontal surfaces, a slight decreasing trend in freeze–thaw events, an increase in growing degree days indicating a small, heightened insect activity, and a rise in heavy precipitation days. The Scheffer Index shows a significantly increased potential for wood degradation, particularly under the RCP 8.5 scenario, while the Wet-Frost Index remains consistently low. Finally, according to each identified hazard, adaptive solutions are suggested. These findings provide critical insights into future climate impacts on heritage buildings in the region, aiding stakeholders in planning targeted interventions. The study emphasizes the crucial role of integrating detailed climate data into heritage preservation strategies, advocating for the inclusion of future risk analysis in the "knowledge path" in order to enhance the resilience of buildings.

Keywords: building heritage; climate change; regional model projections; hazard maps; adaptive solutions; climate-heritage indices

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1. Introduction

The increase in greenhouse gases in the atmosphere poses a significant threat to built heritage through intensified climate-related impacts [1–3]. Although the past two decades have significantly advanced our general understanding of how climate change affects material decay and have explored broad mitigation strategies [1,4–6], a significant gap remains in the availability of actionable tools to support localized, technical interventions. For example, although each Italian region is expected to develop its own climate adaptation strategy [7], the absence of high-resolution climatic hazard data continues to hinder the design of effective, site- and region-specific measures that address diverse climatic challenges and local vulnerabilities. In response to this challenge, the present study proposes and applies a dedicated methodology for generating high-resolution climate-heritage hazard maps. These maps aim to translate climate projections into spatially explicit risk information tailored to heritage needs, offering a practical and scalable tool to support informed decision-making and technical design. By doing so, local authorities are better equipped to develop regional adaptation plans, while heritage professionals can incorporate future climate risks into the design of rehabilitation and restoration interventions.

A closer look at European strategies, national policies, and key research initiatives helps to highlight both the progress made and the critical gaps that still hinder effective climate adaptation for cultural heritage. At the European level, the European Union (EU) recently updated its climate adaptation strategy, with the goal of achieving climate resilience across Europe by 2050 [8]. The strategy emphasizes smarter adaptation, systemic and integrated approaches, swift implementation, and strengthened international cooperation. A central component of this strategy is encouraging each member state to develop a National Plan for Adaptation to Climate Change. At the national level, Italy implemented its National Strategy for Adaptation to Climate Change (SNAC) in 2015 [9], which has been further integrated with the National Recovery and Resilience Plan (PNRR) [10]. The PNRR incorporates policies addressing both climate change mitigation and adaptation. In 2022, Italy introduced its Plan for National Adaptation to Climate Change (PNACC) [11], which stands out, alongside France's and Ireland's plans, as one of the few national strategies to include a dedicated chapter on cultural heritage. This latter draws on findings from two key sources: the ISPRA report on extreme phenomena, namely, hydro-geological hazards [12], and the European Noah's Ark Project [13], which focused on slow-onset degradation processes. The Noah's Ark Project employed climate models from the Hadley Centre, including both global (HadCM3) and regional (HadRM3) models, under the IPCC A2 emissions scenario [14]. The project generated hazard maps based on 30-year averages for three distinct timeframes: the reference period (1961–1990), the near future (2010–2039), and the far future (2070–2099). These maps, along with comparative analyses between periods, provide valuable insights for assessing and quantifying the magnitude of climate change impacts over Europe. However, the project's maximum spatial resolution of 50 km poses a significant limitation, as it impedes the ability to plan site-specific adaptation measures, particularly for regions with complex orographic and climatic conditions. The PNACC, indeed, acknowledges the necessity of downscaling climate impact data to higher resolutions to evaluate risks not only for broader landscapes and historic centers but also for individual cultural heritage assets. Importantly, it highlights a critical gap: to date, there have been no studies specifically addressing the impacts of climate change on Italy's cultural heritage. Given the country's highly diverse and geographically complex landscape, this gap significantly hinders efforts to assess risks comprehensively. The PNACC also advocates for the development of Regional Plans for Adaptation (Piani Locali di Adattamento) [7], tailored to the unique needs of each region. However, a key challenge remains: how can regional and local authorities make well-informed decisions when high-resolution, site-specific data required for cultural heritage impact assessments are currently unavailable? This lack of data continues to obstruct the effective translation of the European and national objectives into actionable, regionally targeted adaptation measures.

To address the current national gap in high-resolution climate risk information for cultural heritage, this study focuses on the Trentino–South Tyrol region in northeastern Italy as a representative case study. Rather than aiming to provide a comprehensive impact assessment of the area, the primary objective is to present an adaptable and replicable methodological framework for developing high-resolution climate-heritage hazard maps. This framework is designed to be transferable to other regional and national contexts. The analysis concentrates on two key climatic variables, temperature and precipitation, derived from a high-resolution daily dataset. Although the scope is limited in terms of the number of climatic variables and the temporal granularity of indices, the results offer a valuable foundation for supporting regional authorities and cultural heritage stakeholders in making evidence-based decisions regarding climate adaptation and risk mitigation.

The region Trentino–South Tyrol was selected due to its complex terrain, diverse and rapidly changing climate [15,16], and high density of historic buildings [17], which make it particularly vulnerable to climate change and in need of high-resolution [18,19] and site-specific adaptation strategies [20]. This study employs high-resolution EURO-CORDEX climate projections, previously downscaled and bias-adjusted to a 1 km grid dataset by the EURAC Research center [21], alongside the open-source climdex-kit [22] to calculate climate-heritage indices and generate detailed hazard maps for three future timeframes, i.e., the reference period (1981–2010), the near future (2031–2060), and the far future (2071–2100). It then proposes adaptive technical solutions based on the identified risks, highlighting the value of integrating scientific data with heritage expertise through a multidisciplinary approach.

The following sections will encompass the following topics: Section 2 (Methodology) explains the conceptual method and the tools used for the purpose of this paper as well as the climate-heritage indices analyzed and chosen according to their dependency on the two climate factors, namely temperature and precipitation; Section 3 (Results) presents the risk maps for each index produced by the model simulations in the three climatological ranges. These latter are divided according to the climate-dependent variable. Section 4 (Discussion and proposed adaptive) discusses the resulting risk maps and proposes possible adaptive solutions for the region of Trentino–South Tyrol in Italy, as well as limitations of this research, and suggests areas for future research. Key characteristics of the selected climate-heritage indices, along with a summary of the regional context using both quantitative and qualitative data, are detailed in the Appendix. Finally, Section 5 (Conclusions) summarizes the main findings of this study, emphasizing the originality of the proposed methodology and its potential for broader application.

2. Methodology

By leveraging the systematic principles of Heritage Climatology [23], this study develops a comprehensive and adaptable methodology for assessing the impact of climate variations on heritage buildings. While this approach is applied to the Trentino–South Tyrol region, it is deliberately designed for broad replicability across different geographical contexts. The approach integrates high-resolution climate data, advanced climate index calculation tools, and detailed risk and adaptive solution mapping to provide a thorough analysis of potential climate-related threats to heritage sites. Figure 1 provides a comprehensive overview of the methodology's flow chart, outlining the sequential steps from the selection of climate data and climate heritage indices for study, to their analysis using the climdex-kit tool [22]. This is followed by the creation of risk maps through the R coding environment for visualization purposes and the proposal of proactive solutions. Each of these steps is explained in detail in the subsequent subchapters. Research data, including index definitions, codes, and results, are available in an open-access GitHub repository (see Supplementary Materials for the link). This methodology aims to give stakeholders a thorough understanding of regional future climatic challenges and to support effective decision-making and the development of effective preservation strategies.

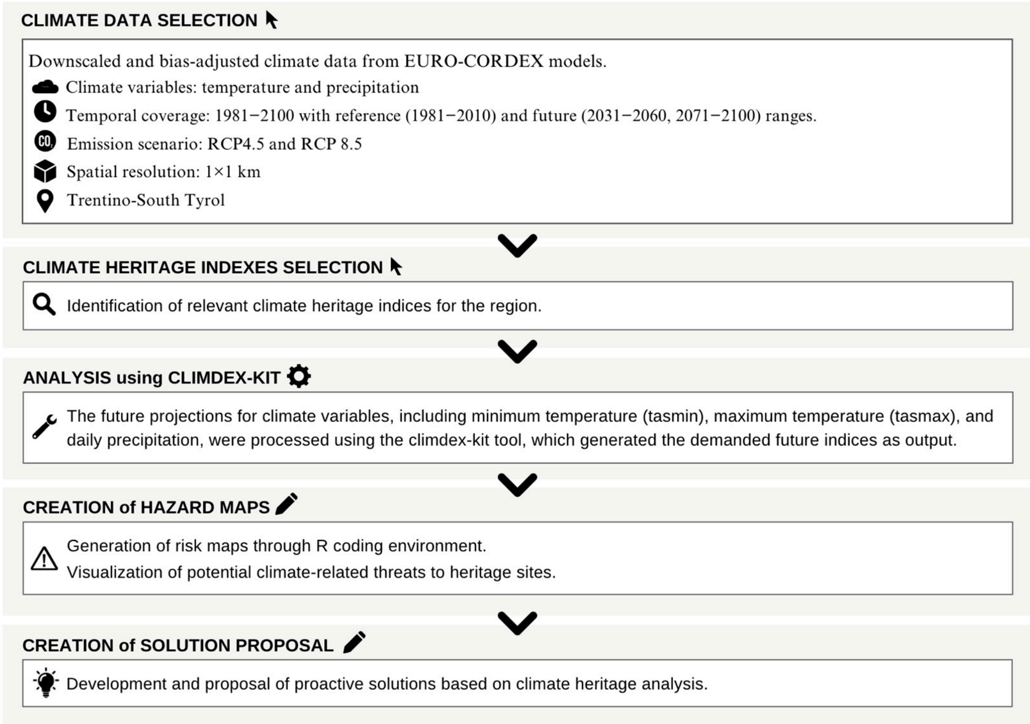

Figure 1. Overview of the adopted methodology.

2.1. Target Geographical Area

Trentino–South Tyrol, the northernmost region of Italy, spans approximately 13,000 km^2 and features a densely varied terrain. The region's average elevation is around 1600 m a.s.l., with altitudes ranging from 65 m to 3900 m a.s.l., encompassing steep slopes and narrow valleys [24]. Its climate is shaped by the interaction of humid air masses from the Atlantic northwest, dry air masses from the continental east, and warm, humid air from the Mediterranean, leading to cold winters and warm summers with significant local variations [19,25–27]. This climatic and topographical diversity results in strong microclimate variability across the region [24], which is crucial to understand for cultural heritage preservation. Various climate conditions expose cultural assets to distinct threats, making high-resolution climate projections, particularly in such a complex topographical region [18,19], crucial for accurately assessing risks to its built heritage. Future projections indicate that the region will experience a significant rise in temperatures and altered precipitation patterns [25], given more frequent heat waves and extreme rainfall events [16,27,28]. Furthermore, the region is home to a diverse array of listed buildings, each with its own unique architectural and historical significance. According to Vincoli in Rete, the most common structural typologies among the region's listed heritage assets include 137 bell towers, 115 chapels, 198 residential buildings, 187 castles, and 506 churches [17]. This rich variety of cultural heritage, combined with the region's complex orography and climatic conditions, underscores the importance of using high-resolution climate projections to accurately assess the risks to these historic structures. This enhanced understanding highlights the Trentino–South Tyrol region, with its two provinces, Bolzano and Trento (see Figure 2), as a critical area of study, particularly given the significant rise in average temperatures [15,16,28].

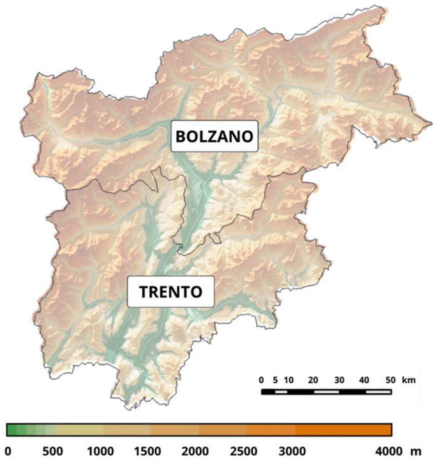

Figure 2. Trentino–South Tyrol region, Italy, with its provinces of Bolzano and Trento. Adapted figure from [27].

2.2. Climate-Heritage Indices

Climate-heritage indices, or climate-based indices [29], are quantitative metrics used to assess the potential impacts of climate change on cultural heritage sites. These include various climatic factors such as temperature, precipitation, humidity, and extreme weather events, which can affect the preservation and integrity of heritage buildings and monuments [4,30,31]. The selection of these indices was based on a comprehensive review of existing indices used in various international projects, such as Noah's Ark [32] and Climate for Culture [33], many of which are part of the core set defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) [34], alongside individual studies [35]. These were integrated with projected regional climatic data, adjusted for bias by other studies in the region [22]. Given that the existing high-resolution dataset used in this study included only precipitation and temperature data with daily temporal resolution, the indices were selected based solely on these two parameters and their relevance to the regional context. Notably, the Consecutive Dry Days (CDD) index [5,36–38], which reflects potential impacts from the shrinkage and swelling of clay-rich soils, was excluded from this analysis, as the presence of clay soils in the region does not pose a significant hazard risk of this nature [39]. Furthermore, special attention was given to indices that assess the potential degradation of materials typical of regional heritage sites, such as wood and stone [25]. Consequently, taking all these factors into account, climate indices relevant to external threats to historic buildings in the Province of Bolzano and selected for this paper were limited to eight specific ones:

- Lichen Species Richness (D);
- Freeze–Thaw Cycles (FTCs);
- Growing Annual Degree Days (GDD15);
- Heavy Precipitation Days with above 10 mm rain (R10);
- Heavy Precipitation Days with above 20 mm rain (R20);
- Wet-Frost Index (WFI);
- Scheffer Index (SCHIX);
- Biomass Accumulation (B).

Among these indices, FTC and WFI assess the risk of stone and brick degradation, SCHIX and GDD15 focus on biological decay due to temperature-dependent insects and fungal attack on wood, while the remaining four indices apply to various materials (see Figure 3, center). Additionally, as detailed in Section 3, the first three indices are temperature-dependent, the next two are precipitation-dependent, and the final three are influenced by both climatic variables (see Figure 3, left). It is worth noting that the SCHIX index, while valuable, does not fully capture the risk of biological decay, as this also depends on relative humidity (RH), a climatic factor not included in SCHIX nor in the present study. Finally, the last pie chart in Figure 3 displays the distribution of degradation types across the selected indices. Definitions, formulas, and references for these indices are provided in the final Appendix A Table A1. Except for GDD15, SCHIX, R10, and R20 [13,40,41], past studies focusing on Europe generally expect a decline (for FTC and WFI) or a constant condition (for B) in these indices [13,40]. However, the same studies on the WFI, FTCs, and B suggest that northern and high-altitude areas might experience an increase [4,13]. Additionally, regions with dense orographic conditions have diverse macroclimates, leading to significant climate variations and necessitating detailed local analysis [18]. Vandemeulebroucke also notes that changes in climate variables are not uniform across different regions [29]. These findings highlight the need for region-specific studies and conservation strategies to effectively mitigate climate-induced damage to heritage sites.

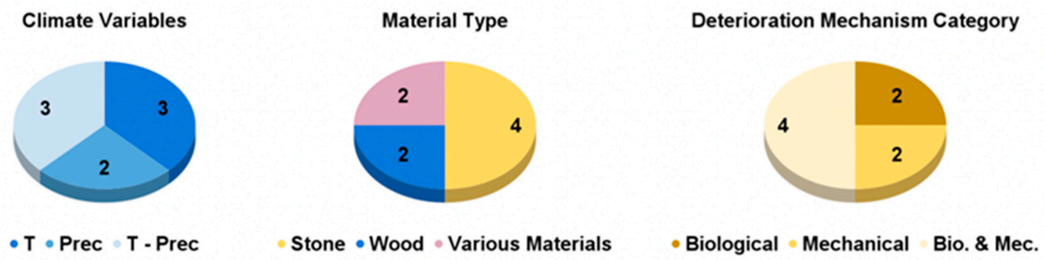

Figure 3. Categories of the climate indices selected for this research (total: eight). Numbers and proportions (through pie charts) of the indices: based on (**left**) different groups of climate variables, (**center**) materials affected by the index phenomena, and (**right**) different categories of deterioration mechanisms.

2.3. Climate Data

This study utilized a downscaled and bias-adjusted version of a subset of EURO-CORDEX climate simulations (originally at $0.11^\circ \times 0.11^\circ$ resolution on the European EUR-11 domain [42]). The original dataset was resampled through bilinear interpolation to a 1 km grid dataset, and bias-adjusted against the observation gridded climate dataset available for Trentino–South Tyrol [21]. The utilized dataset was also used and assessed in previous local applications requiring tailored climate-change scenarios for South Tyrol [16,22]. In particular, the dataset is derived from an ensemble of projections from eight Regional Climate Models (RCMs) for the period 1971–2100, based on the Representative Concentration Pathways (RCP) 4.5 and 8.5, which represent the intermediate and worst-case future emission scenarios, respectively, according to the 6th IPCC Assessment Report (AR6) [40,42]. It is important to note that, as the current version of EURO-CORDEX is based on CMIP5 [43], the simulations are based on RCPs rather than on the newer shared socioeconomic pathways (SSP) scenarios outlined in the IPCC AR6, which integrate socioeconomic pathways alongside emissions trajectories.

Table 1, adapted from Campalani [22], provides details of these eight RCMs, including their realization, version, and the corresponding General Circulation Model (GCM) from which they inherit. Indeed, the ensemble approach is particularly valuable in reducing the influence of individual model biases and thus ensuring more reliable future projections [44]. For a more detailed description of the data source, please refer to Campalani [22]. The climate variables utilized in this study as the basis for the calculation of climate indices encompass daily minimum (Tas,min) and maximum temperature (Tas,max), and daily total precipitation (p) [22].

Table 1. Ensemble of regional climate models (RCMs) used in this study adapted from [22].

GCM	RCM	Realization	Version
CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17	r1i1p1	v1
CNRM-CERFACS-CNRM-CM5	CNRM-ALADIN63	r1i1p1	v2
CNRM-CERFACS-CNRM-CM5	KNMI-RACMO22E	r1i1p1	v2
ICHEC-EC-EARTH	CLMcom-CCLM4-8-17	r12i1p1	v1
ICHEC-EC-EARTH	KNMI-RACMO22E	r12i1p1	v1
IPSL-IPSL-CM5A-MR	IPSL-WRF381P	r1i1p1	v1
MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	r1i1p1	v1
MPI-M-MPI-ESM-LR	MPI-CSC-REMO2009	r1i1p1	v1

2.4. Future Climate-Heritage Index Calculation

The open-source climdex-kit tool [22] was used to compute the climate-heritage indices based on downscaled, bias-corrected temperature and precipitation data for the period 1971–2100 under the RCP 4.5 and RCP 8.5 scenarios. This tool also allowed for the analysis and visualization of these indices, comparing them across three distinct time periods: the reference period (1981–2010), the Near Future (2031–2060), and the Far Future (2071–2100).

Climdex-kit (version 1.0.0) combines Climate Data Operators (CDO) [45] and Python functionalities to perform the calculation, analysis, and visualization of climate indices and their variability. It supports a variety of predefined indices but also allows users to customize calculations for additional indices. The tool accepts input data in netCDF format, the standard in climate science, which enables storing a large amount of data together with metadata describing the data product, enabling efficient processing. The computation instructions for each index, including descriptions, units, and other metadata, are stored in an editable configuration file, allowing for customization. For more details on the indices' definitions, refer to the repository on GitHub. Input climate data, structured by variables and scenarios in netCDF files, are processed by climdex-kit, and the outputs are also stored in individual netCDF files for each model [22].

To analyse the computed indices and their variations, the R programming environment [46] was employed. This enabled the generation of maps showing regional climate risks in Trentino–South Tyrol, highlighting areas most vulnerable to climate impacts. The visual outputs included the following:

- Maps showing the climatological values of each index;
- Boxplots illustrating the range of projections from different models for each index;
- Maps displaying relative anomalies, which show deviations from the reference period's climatological averages;
- Additional maps of the climatological values of each index, complemented by an indication of the significance of projected changes under future scenarios, are defined by the agreement among ensemble models. For simplicity, these maps are hereafter referred to as "significance maps".

The color schemes and value ranges used in the maps were informed by previous studies, such as the Noah's Ark project [13], to ensure comparability. The available benchmarks used for the color discretization of the indices [47,48] are detailed in Appendix A Table A1. Boxplots were used to highlight the variability between models, offering insight into the consistency and reliability of the projections. Significance maps mark those areas where less than 65% of the models agree on the sign of projected change relative to the reference period 1981–2010. These areas, marked with a black mask overlayed on the climatological maps, should be analyzed with caution. The methodology used for these maps is the same used in the IPCC's AR6 [40]. If no significance maps are present for certain indices, at least 65% of the models considered agree on the sign of the projected change over all regions.

Because precipitation totals vary significantly within the region, due to different climate contributions and orography, we complemented the graphs for heavy precipitation indices (R10 and R20) with maps displaying the relative anomaly of the indices with respect to present climate. This is defined as the difference between the average value of the index under future scenarios and the current climate, scaled by the average value under the current climate.

This study also proposes adaptive strategies to mitigate the projected negative impacts of climate change on heritage buildings. These strategies, informed by existing research [6], are detailed in Appendix A Table A3, which lists the projected indices, the regional consequences, and potential solutions aimed at reducing the risks identified by the climate-heritage indices.

3. Results

In the following chapter, each climate-heritage index (D, FTC, GDD15, R10, R20, SCHIX, WFI, and B) is thoroughly analyzed through risk maps across the climatological periods 1981–2010, 2031–2060, and 2071–2100 under RCP 4.5 and RCP 8.5 emission scenarios. Detailed information on these indices, including definitions, acronyms, formulas, and reference studies, can be found in Table A1 of the Appendix. Additionally, each range of values in the climatological maps is accompanied by a legend indicating the percentage of the region's area that falls in that range. Quantitative data on Regional Climatology and Regional Relative Change are provided in Table A2, including the mean regional value and the range of values across the region [min; max] in brackets for each index under both RCP scenarios. These data cover the Reference Period (1981–2010), Near Future (2031–2060), and Far Future (2071–2100), with all relative changes referenced against the Reference Period to highlight projected regional changes. Additionally, qualitative interpretation of the risk maps, impacts of the changing indices, and potential solutions are summarized in Table A3. Together, these projections offer stakeholders critical insights into future regional climate impacts, helping heritage site managers identify targeted interventions to protect culturally and historically significant assets.

3.1. Temperature-Derived Indices

3.1.1. Lichen Species Decay

When lichens cover tangible heritage surfaces, they influence the aesthetic impact and simultaneously play both deterioration and protection roles [49,50]. According to the Noah's Ark project [13], lichen species richness is expected to decrease across almost all of Europe in both the near and far future. This study observes, in Trentino–South Tyrol, a potential decline in the lichen species richness index (D), particularly under the RCP8.5 emission scenario. While some lichen species can withstand high temperatures, most are known to die at stone surface temperatures between 45–65 °C [51]. Indeed, pasteurization occurs at 63 °C for 30 min or at 72 °C for 15 s [52,53], corresponding to periods with 20–35 °C air temperatures when exposed to the sun [54,55]. As temperatures significantly increase in this region [15], they will likely reach levels that threaten lichen survival. However, it must be noted that McIlroy de la Rosa observed, in their case study research, that it is the average stone surface temperature of approximately 21 °C over a year, and not punctual high peaks, that determines lichen presence on stoneworks [35].

Using the empirical model developed within the Noah's Ark project framework, this study demonstrates a significant decline in D (Figure 4), especially in the main valleys (Figure 5), with the impact spreading to smaller valleys and exacerbating conditions in larger valleys over time, since there are higher temperatures. In the distant future, under the worst-case emission scenario, lichen populations are projected to decrease regionally by up to 15.3% compared to the reference period (see Table A2), and this may extend to higher altitudes. All models of the ensemble agree on the decline of the index in the region, as shown by the models' boxplot (see Figure 4) and the significance map, which is not displayed here because all models agree on the sign of projected change over the entire region. Changes in lichen richness impact not only the aesthetic and material condition of stone surfaces but also reflect a broader biodiversity decline, as saxicolous lichens are key biodiversity indicators [13]. Furthermore, it must be said that the exact effects of increased or decreased lichen species on material deterioration or protection of construction stones remain uncertain, although usually not damaging [56], and the aesthetic impact of these changes can be subjective [13].

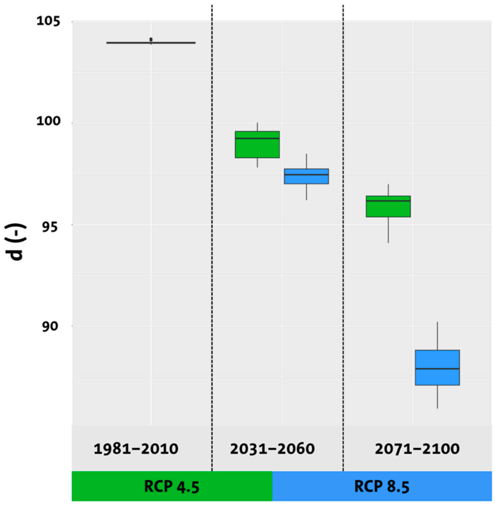

Figure 4. Boxplot of the regional average values of the lichen species richness (d) index, averaged over the three reference periods. Color fillings indicate projection under scenario RCP 4.5 (green) and projection under scenario RCP 8.5 (blue).

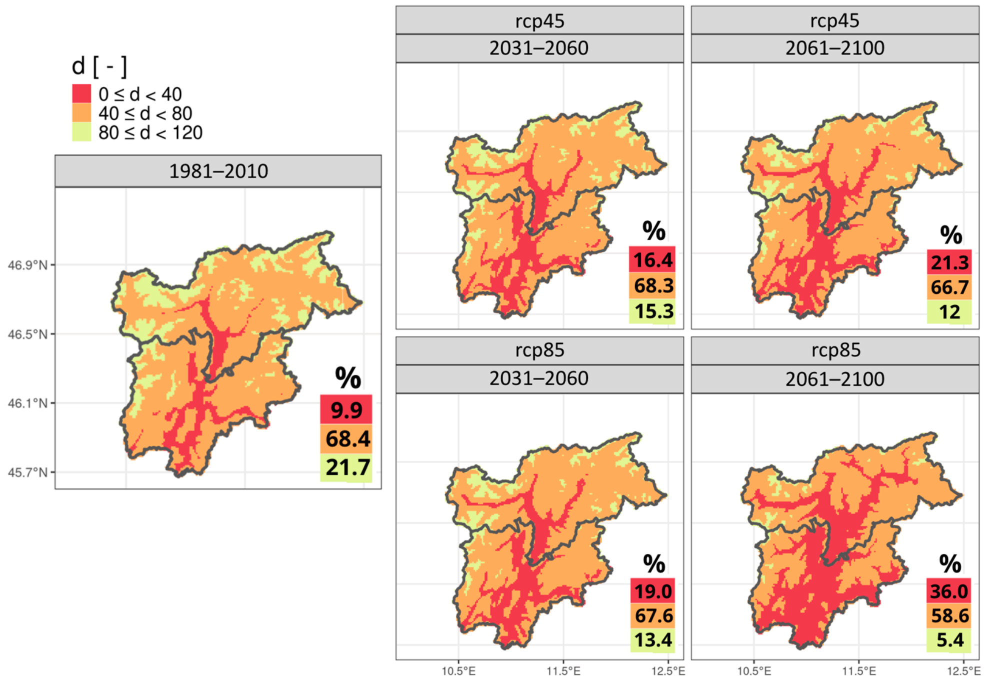

Figure 5. Maps of climatological values of the lichen species richness index under the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios for three time periods: (**left**) 1981–2010, (**middle**) 2031–2060, and (**right**) 2071–2100.

3.1.2. Frost Damages (Freeze–Thaw Cycles, FTCs)

When water transitions from liquid to solid within porous masonry or structural cracks, it expands, causing damaging stress [57]. Repeated cyclic stress weakens the brick or stone, eventually leading to frost weathering or damage such as delamination, spalling, grain loss, flaking, or crumbling of the outer surface [47,58,59]. Furthermore, freeze–thaw cycles (FTCs) can destabilize buildings, roads, pipes, and bridges due to frost heave, subsidence, and thaw settling [60–63]. On a broader scale, alterations in slope stability can elevate the frequency of landslides during thawing in mountainous regions [61,64,65]. It is for these multiple reasons that it is important to study the future variations of this phenomenon in this case study region. Past studies found that the number of FTCs in much of Europe is expected to decrease in the future [13]. However, certain areas, such as the far north or high altitudes, may see an increase in cycles (Brimblecombe P. and Grossi, 2011 [66]; Viles, 2002 [67]) with regional [68] and local variations influenced by factors like urban heat islands or specific building locations [69–71]. Considering the diverse definitions of FTCs available, this study used three distinct definitions in the analysis in order to validate the findings comprehensively. However, due to space limitations, only the risk map based on the definition of Richards [72] is presented. In the Noah's Ark project, the FTC is defined as the number of days in a year with minimum temperature (T_{min}) at or below -3 °C and a maximum temperature (T_{max}) at or above +1 °C, while the more recent study of Richards and Brimblecombe defined FTC as the number of days when $T_{min} < 0$ °C and $T_{max} > 0$ °C [72] (in our study we consider this definition). Finally, a third definition measures the number of freezing events (D_n) per year where the mean temperature (T_{mean}) drops below 0 °C, provided the previous day (D_{n-1}) was not frosty, i.e., D_n ($T_{mean}< 0$ °C) and D_{n-1} ($T_{mean} > 0$ °C) [30,69]. Although they all result in values belonging to different value ranges, they all show that there is a considerable decrease in FTC events (up to -24%, see Table A2), especially in the valleys where temperature is expected to rise above the hovering range where FTCs can take place. In the distant future, under worse emission scenarios, higher temperatures could be observed in narrow valleys where shadows typically lower temperatures. As a result, these areas may experience a reduction in FTCs. However, with these assumptions, there is no clear benchmark to define when decay occurs in different materials. This would be a valuable point of study.

While models agree on the projected overall decrease of the index in the region (Figures 6 and 7a), uncertainty on the magnitude of such a decrease becomes high at the end of the century (i.e., Far Future) under RCP 8.5, as shown by boxplots in Figure 6. As also explained by Richards [72], this big uncertainty of variables based on a cycle over a set temperature threshold, for instance, FTCs, is due to even small temperature biases in the model that can cause notable changes in the number of times the temperature crosses a threshold. In conclusion, rising temperatures will substantially reduce the number of days when the temperature hovers around zero. However, in high mountains, the number of days where the temperature hovers around zero remains high, and the models show a small variation, with conflicting signs (see Figure 7b). Therefore, we can conclude that, in high mountains, the reduction of this index is not significant.

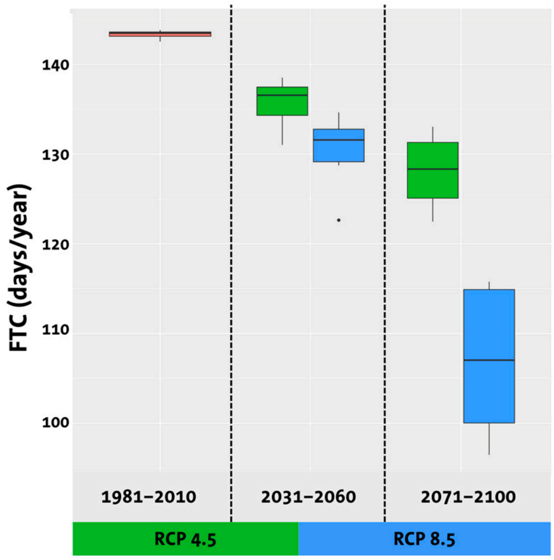

Figure 6. Boxplot of the regional average values of the freeze-thaw cycles (FTC) index, averaged over the three reference periods. Color fillings indicate historical simulation (red), projection under scenario RCP 4.5 (green) and projection under scenario RCP 8.5 (blue).

3.1.3. Biological Decay (Temperature-Dependent Insects) on Wood

Some insects can affect timber elements of heritage buildings [73,74], such as powderpost beetles, death watch beetles, also known as woodworms, carpenter ants, and flatheaded borers [75–77]. Growing Degree Days (GDD) is a measurement of heat units over time, indicating the number of degrees the average temperature exceeds a baseline value [78], and it can reflect biological processes of temperature-dependent insects. Indeed, research shows that insect inactivity, e.g., reduced mating and flying [79,80], happens below 15 °C (hence the acronym GDD15) and above 30 °C [80,81]. This means that even modest changes in temperature have the potential to alter insect lifecycles and numbers [75,79,82], also changing their capacity to damage historical materials [47].

According to past studies, all of Europe shows, throughout the 21st century, increasing values of GDD15 [74], which will likely increase the insects' growth cycles. This study reveals, through the boxplot (see Figure 8), climatological maps (see Figure 9), and the percentage values in Table A2, that while the average value for the region increases substantially, it still remains within the very low range of conducive levels according to Loli's discretization [47]. However, the climatological map shows that there is, in line with previous studies, a steep increase in the valleys, due to the expected higher temperatures. All models of the ensemble agree on the projected increase in the index in the region, as shown in the boxplots in Figure 8. In particular, the light increase in the risk of biodeterioration of wooden construction elements due to insect activity in valleys is reliable, with models agreeing on the magnitude of change, while the increase projected for higher and colder areas of the region is non-significant (see Figure 9b).

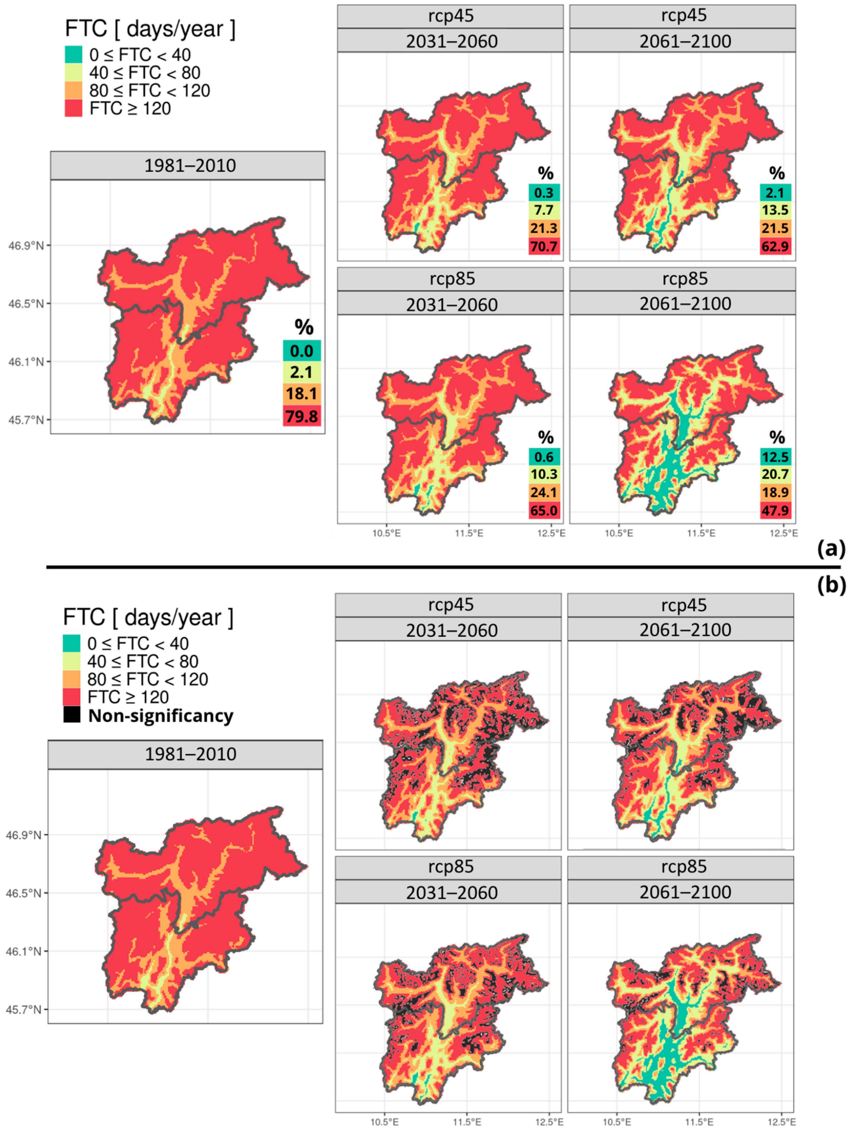

Figure 7. (**a**) Maps of climatological values of freeze–thawing cycles (FTC) under the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios for three time periods: (**left**) 1981–2010, (**middle**) 2031–2060, and (**right**) 2071–2100. (**b**) Same maps as in (**a**) with black mask indicating areas with non-significant projected change relative to the baseline period 1981–2010.

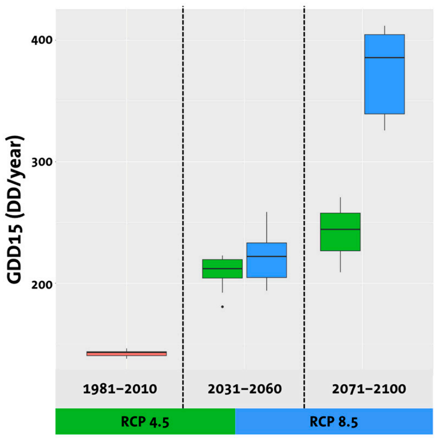

Figure 8. Boxplot of the regional average values of the Growing Degree Days 15 (GDD15) index, averaged over the three reference periods. Color fillings indicate historical simulation (red), projection under scenario RCP 4.5 (green) and projection under scenario RCP 8.5 (blue).

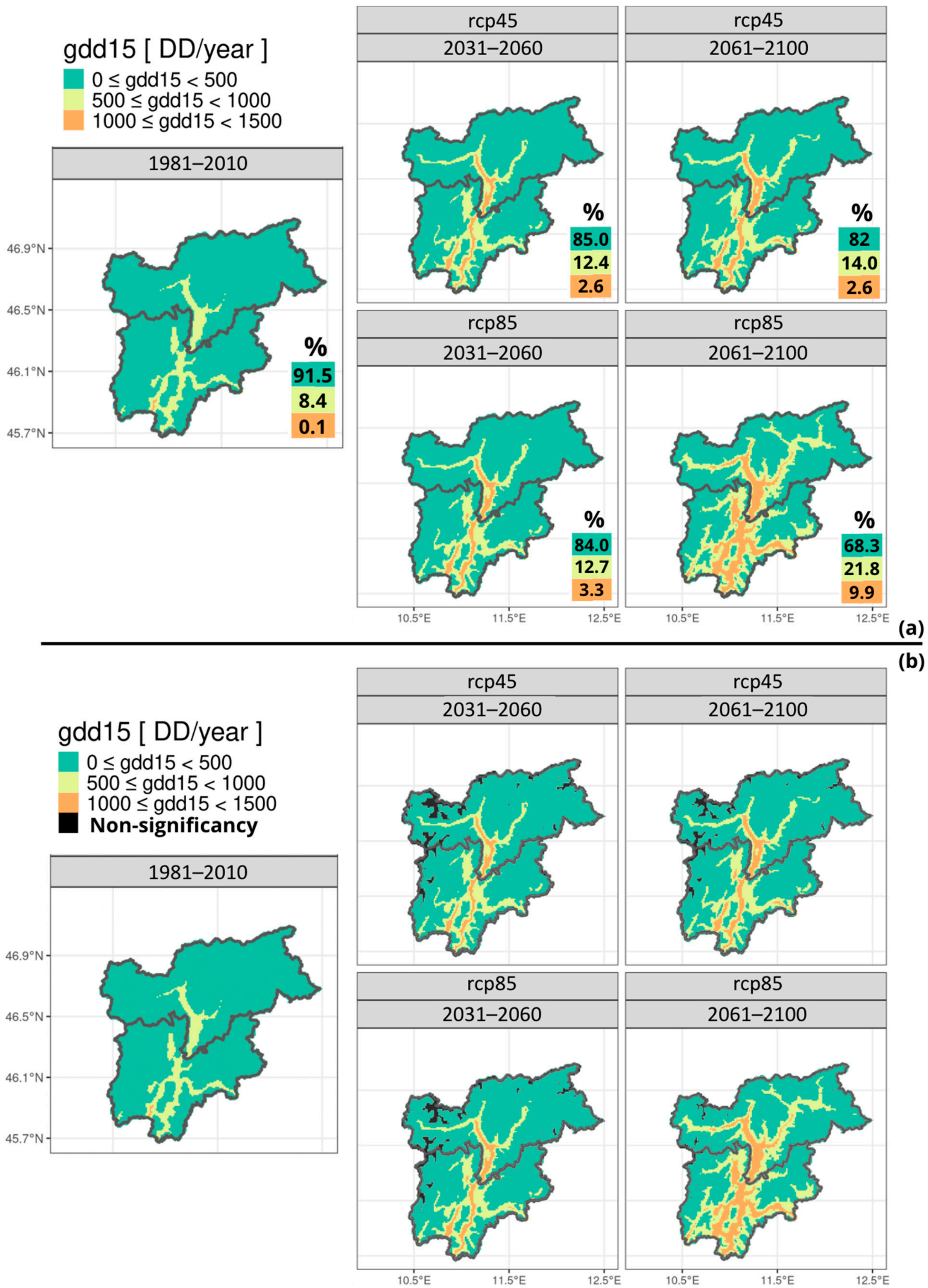

Figure 9. (**a**) Maps of climatological values of the growing degree days index (GDD15) under the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios for three time periods: (**left**) 1981–2010, (**middle**) 2031–2060, and (**right**) 2071–2100. (**b**) Same maps as in (**a**) with black mask indicating areas with non-significant projected change relative to the baseline period 1981–2010.

3.2. Precipitation-Derived Indices

Heavy Precipitation Days (with Pr > 10 mm and Pr > 20 mm)

The Heavy Precipitation Days Index measures the number of days per year with daily precipitation exceeding a set threshold (for example, the 95th percentile of daily precipitation records) [5,41]. Here, in this study, two distinct thresholds were considered: days with precipitation over 20 mm (R20), which are categorized as 'rare' events [83] and have been observed to increase globally [83,84], and days with precipitation exceeding 10 mm (R10). Although less severe, these R10 events are also showing a rising trend over time [85,86].

Such heavy precipitation events pose significant risks to heritage buildings, mainly through water penetration into building materials and the overloading of rainwater disposal systems, including roofs, gutters, hoppers, and downpipes. This can lead to issues like salt crystallization, mold formation, stone recession, and, ultimately, structural damage [5]. Analyzing this index in detail is crucial, especially in mountainous regions where precipitation patterns are more complex and dynamic [87,88]. While overall rainfall may decrease in Europe, intense downpours are expected to become more frequent in the future [13,89–92]. Existing studies demonstrated that Bolzano's Province expects an increasing intensity of heavy precipitations [93].

The boxplots in Figure 10 indicate an increase in the frequency of heavy precipitation events in the region, although with low agreement among models regarding the magnitude of such an increase, which is of the order of 2 days/year. Indeed, climatological maps (visualizing the median across models) do not show substantial changes in heavy precipitation throughout the century under different emission scenarios for both R10 and R20 (see Figures 11a and 12a). Additional maps of relative anomalies (see Section 2.3 Climate data) have been created (see Figures 13 and 14) to visualize if and where any projected change in the frequency of heavy precipitation events is substantial with respect to the baseline (i.e., over the reference period) value. These maps, along with the quantitative values in Table A2, suggest varying future precipitation patterns between R10 and R20, with the latter showing a substantially greater relative increase. Additionally, the patterns differ between the Province of Trento and the Province of Bolzano. While the Province of Trento experiences a higher number of heavy precipitation events in the current climate (see Figures 11a and 12a), the frequency is not expected to increase substantially over time and across different emission scenarios. In contrast, the province of Bolzano, recording a lower number of heavy precipitation events than Trento in the current climate, is expected to be hit more frequently in the future, with most areas projected to experience an increase in R20 by 10% to 25% with respect to the reference period. Finally, the projected changes in Trentino are mostly non-significant, with small expected variation. In Alto Adige, where the expected variation is positive and higher, the agreement of models on the sign of change is high (see Figures 11b and 12b).

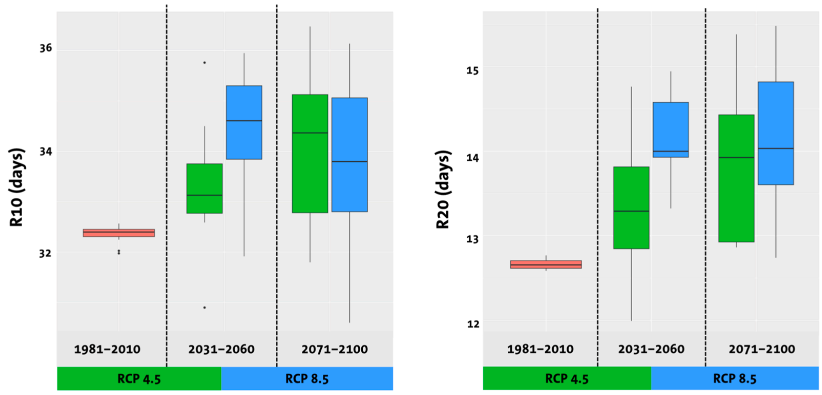

Figure 10. Boxplots of the regional average values of the heavy precipitation indices, R10 (**left**) and R20 (**right**) indices, averaged over the three reference periods. Color fillings indicate historical simulation (red), projection under scenario RCP 4.5 (green) and projection under scenario RCP 8.5 (blue).

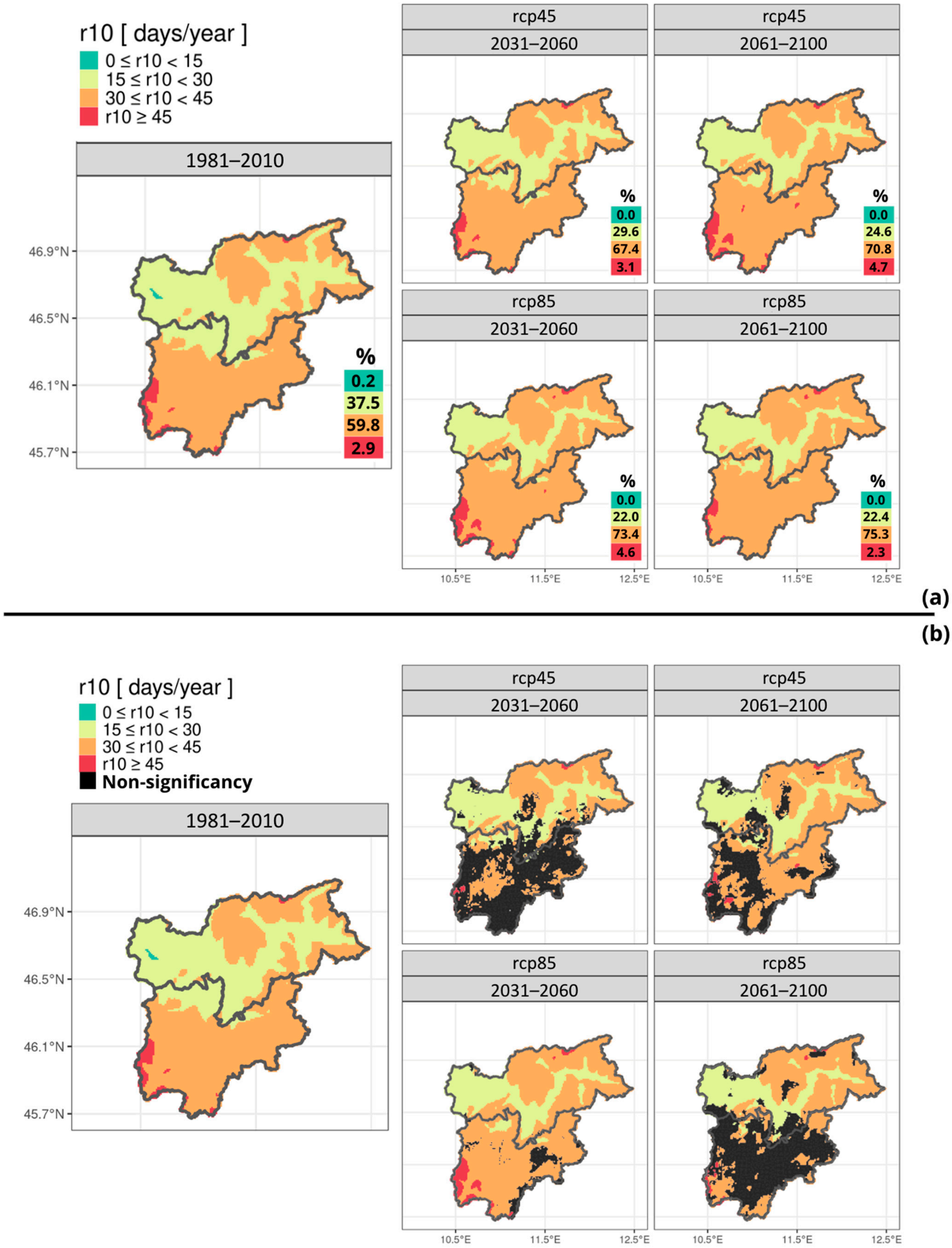

Figure 11. (**a**) Maps of climatological values of the risk of heavy precipitation R10 under the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios for three time periods: (**left**) 1981–2010, (**middle**) 2031–2060, and (**right**) 2071–2100. (**b**) Same maps as in (**a**) with black mask indicating areas with non-significant projected change relative to the baseline period 1981–2010.

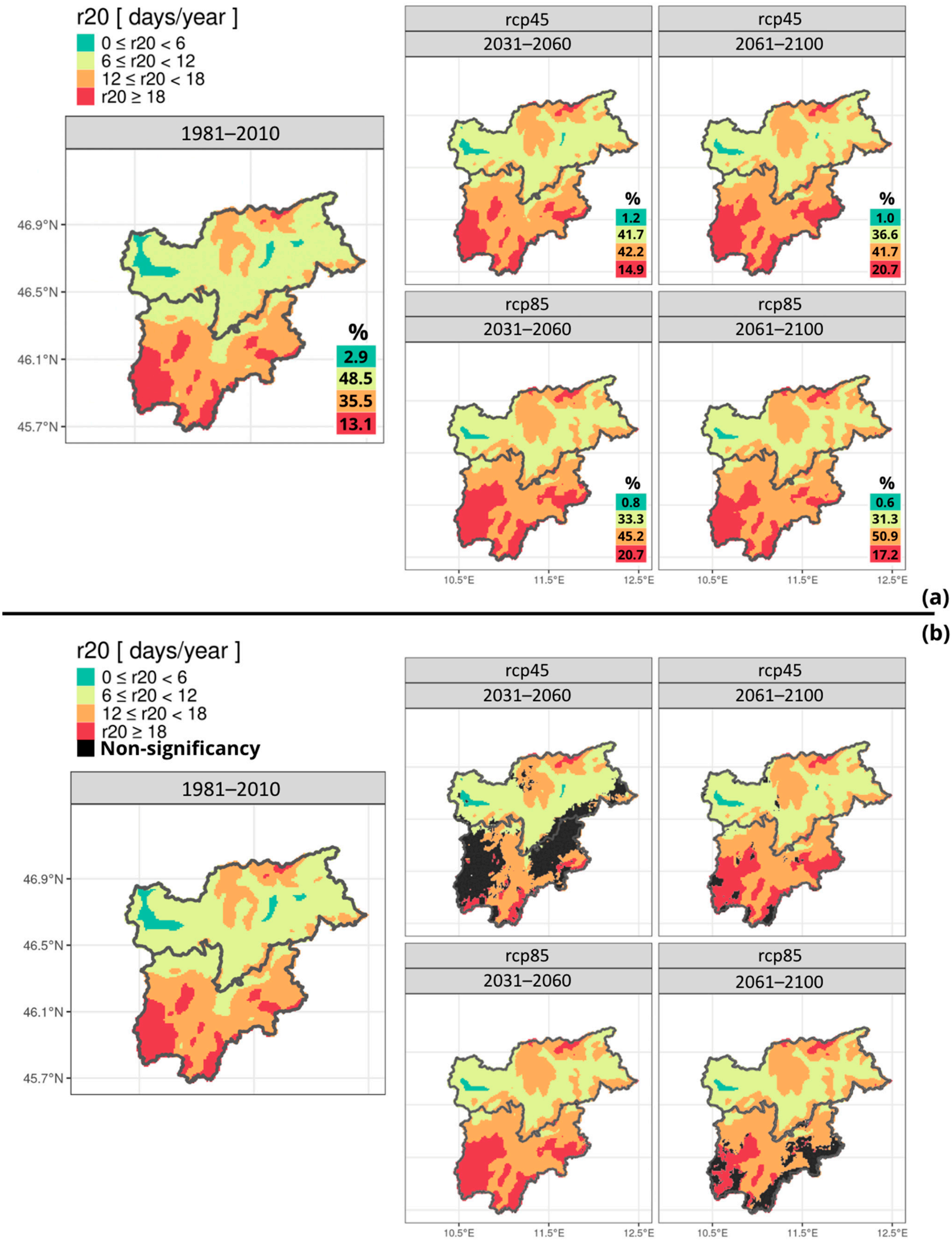

Figure 12. (**a**) Maps of climatological values of the risk of heavy precipitation R20 under the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios for three time periods: (**left**) 1981–2010, (**middle**) 2031–2060, and (**right**) 2071–2100. (**b**) Same maps as in (**a**) with black mask indicating areas with non-significant projected change relative to the baseline period 1981–2010.

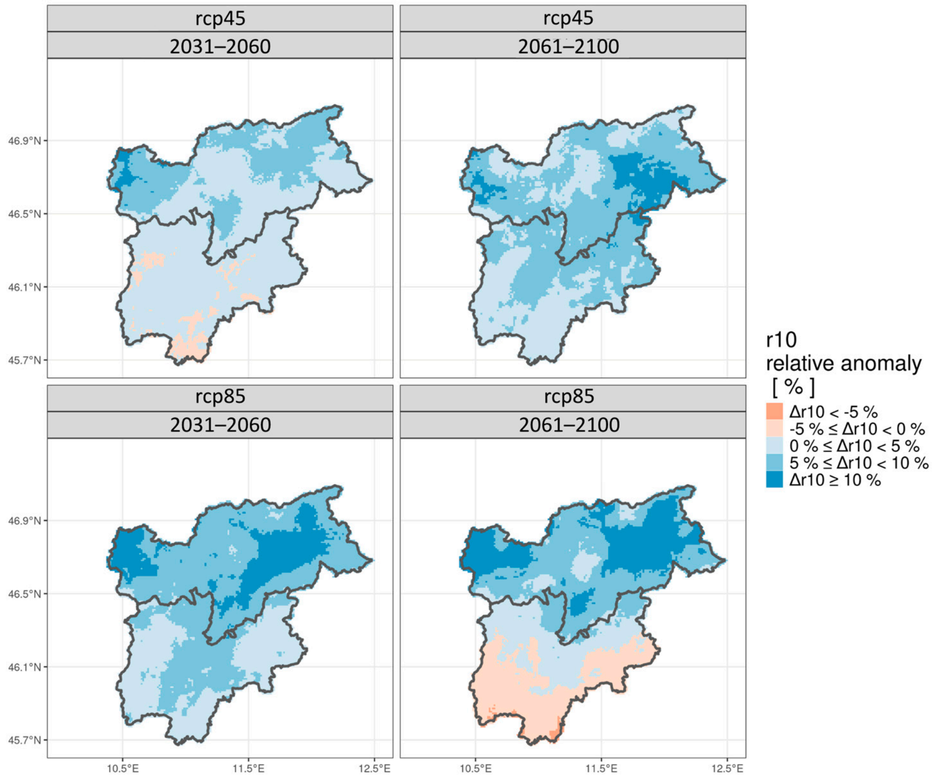

Figure 13. Maps of relative anomaly values of the risk of heavy precipitation R10 in comparison to the reference period under the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios for time periods (**left**) 2031–2060 and (**right**) 2071–2100.

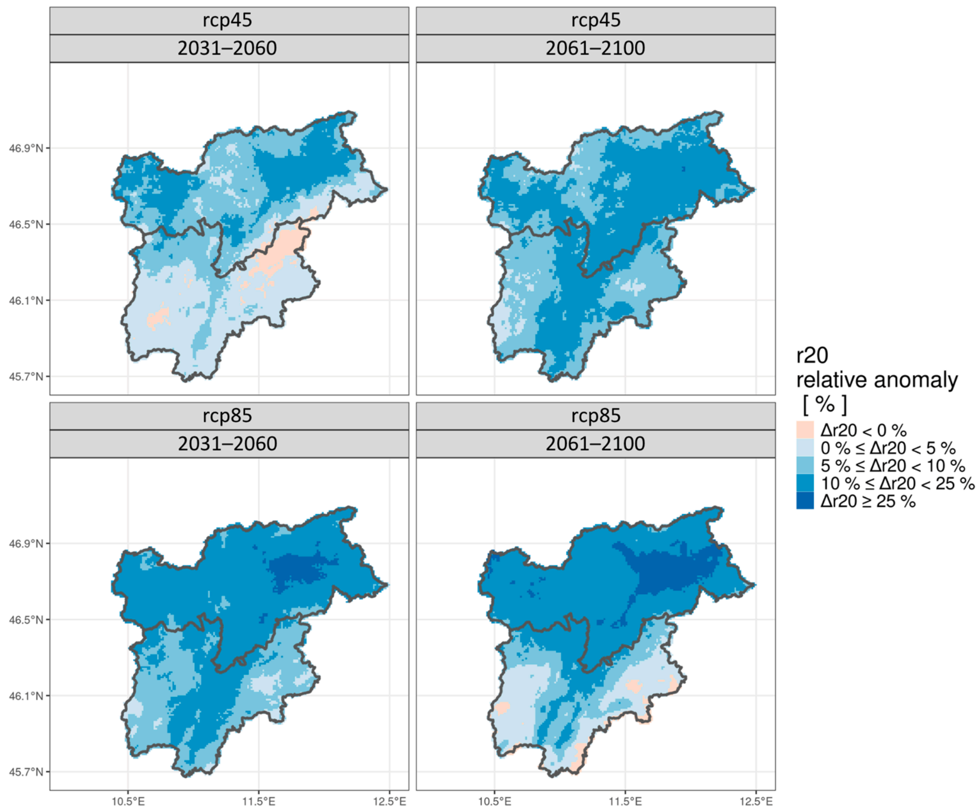

Figure 14. Maps of relative anomaly values of the risk of heavy precipitation R20 in comparison to the reference period under the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios for time periods (**left**) 2031–2060 and (**right**) 2071–2100.

3.3. Temperature and Precipitation-Derived Indices

3.3.1. Frost Damages (Wet Frost Index, WFI)

The increase in the volume of the water contained in the microvoids within the material causes frost damage, such as crack propagation [69], wedging, spalling, surface deterioration (scaling), pitting or roughening, cracking, loss of material strength, and disintegration [13,69]. The potential risk of this mechanical damage in stone and porous materials can be quantified with the wet frost index (WFI), which is defined as the number of days (D_n) in a year with rain (Pr) and positive temperature values, followed immediately by days (D_{n+1}) with a negative temperature. In the context of the Noah's Ark project and other individual studies, the definition used for creating the risk maps was D_n (Pr > 2 mm and $T_{mean} > 0$ °C) and D_{n+1} ($T_{mean} \leq -1$ °C) [4,30,69], while the more recent study of Richards and Brimblecombe parametrized this frost index by using the conditions D_n (Pr > 0.2 mm and $T_{min} > 0$ °C) and D_{n+1} ($T_{min} < 0$ °C) [72]. The parametrization adopted in this paper resembles to those found in the literature, but it also takes into account that macrogelivation happens with temperature below 0 °C (i.e., T < 0 °C) and microgelivation starts with temperatures between −1 °C and −4 °C [94], while, for an effective growth of cracks in stone, temperatures to be reached are between −4 °C and −15 °C [95]. Consequently, the Weathering Freeze Index (WFI) used in this study is defined as the number of days per year when precipitation exceeds 2 mm and the mean temperature is above 0 °C, immediately followed by a day with a minimum temperature of −3 °C or lower, denoted as D_n (Pr > 2 mm and $T_{mean} > 0$ °C) and D_{n+1} ($T_{min} \leq -3$ °C).

According to Noah's Ark results [13], much of Europe will probably experience a reduction in wet-frost, except for the northern part of the European continent, such as Russia, and higher altitudes, which may expect more wet-frost phenomena. This study confirms this trend for Trentino–South Tyrol (see Figure 15), with reductions projected to be especially strong at the end of the 21st century under scenario RCP 8.5 (Table A2, −40 % as a regional average of the projected change with respect to historical period). WFI values at the high altitudes will remain comparable to the average value over the historical period (Figure 16a). The boxplots in Figure 15 reveal a high level of uncertainty on the magnitude of the projected decrease; however, the model agreement on the sign of change is high and the portion of the region with significant projected negative change increases with time and the worsening of emission scenario (see Figure 16b). In addition to the reason already explained for FTC, the uncertainty associated with the change in WFI is due to the combined effect of temperature range biases and the intrinsic uncertainty in rainfall projections [72,96]. Finally, it should be noted that the absolute differences between the values are, at most, 2 units: this questions whether this small reduction would have a real positive impact on stone surfaces, as no benchmark ranges for this definition currently exist.

3.3.2. Biological Decay (Fungal) on Wood

The potential risk of decay in wood due to the effect of wood-degrading fungi [97] is estimated with the Scheffer index (SCHIX). The formula used in this study is adapted from the original one of Scheffer [48] (see Appendix A Table A1), by considering Pr = 0.2 mm, rather than Pr = 0.25 mm, as suggested by other studies focusing on the European zone [97,98]. Furthermore, since this formula calculates the cumulative risk of fungi attacking wood and the subsequent decay, any negative values resulting from the monthly mean temperature multiplied by the number of rainy days are disregarded. As other studies did, these negative values are set to zero to ensure they do not skew the final SCHIX value [18,97,99]. The original scale of Scheffer has been used here for the visualization of climatological values: least favourable conditions for decay (SCHIX < 35), intermediate conditions (35 ≤ SCHIX ≤ 65), and conditions most conducive for decay (SCHIX > 65). Calculating the SCHIX is simple and reliable for predicting rot decay in above-ground outdoor wood, as demonstrated by other studies [99,100]. Therefore, it is considered to be suitable for general use in wood constructions [101] and for heritage managers to estimate the spatial risk distribution to timber, its likely future direction, and strategies to be adopted [98]. However, Brischke demonstrates that small-scale differences in climate-induced decay doses in highly mountainous regions can significantly reduce service lives by up to a factor of 1.5 [18]. Therefore, conducting the study on Trentino–South Tyrol is of critical importance.

Previous studies had demonstrated that SCHIX will increase across the Alps in the future [98], a finding that this study confirms. Figure 17 shows the general projected increase of SCHIX values, as a regional average, across all future scenarios. The increasing trend is projected to be especially strong at the end of the 21st century under scenario RCP 8.5 (Table A2, +50% as a regional average of the projected change with respect to historical period). The condition most conducive to decay is reached in the main valleys in the far future under RCP 4.5, extending to even the narrowest and smallest valleys under RCP 8.5 (Figure 18). All models of the ensemble agree on the increase in SCHIX in the region, as shown in Figure 17, although higher uncertainty associated with modeled values is seen for the RCP 8.5 scenario. No significance map is included for SCHIX, as the agreement among models on the projected sign of change is high. In conclusion, the results for SCHIX suggest that, in the coming years, a higher decay hazard can be expected for wood elements.

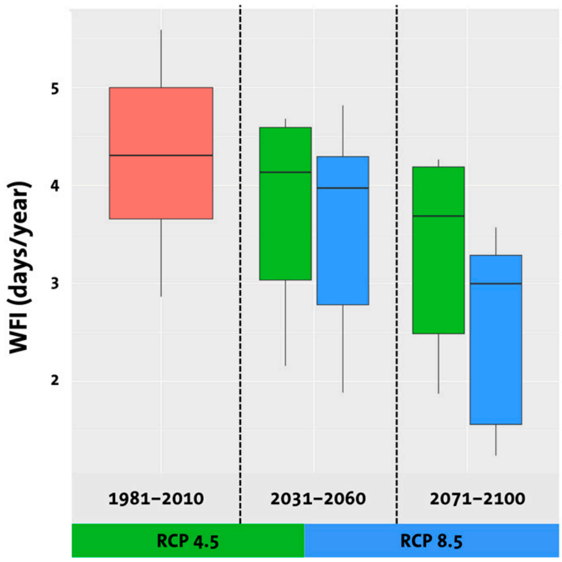

Figure 15. Boxplot of the regional average values of the wet-frost index (WFI), averaged over the three reference periods. Color fillings indicate historical simulation (red), projection under scenario RCP 4.5 (green) and projection under scenario RCP 8.5 (blue).

3.3.3. Biomass Accumulation

Biomass accumulation (B) refers to biological materials on stone surfaces, primarily composed of biofilms including fungi, algae, bacteria, and lichens. Similar to lichens, this biomass can colonize stone surfaces and either deteriorate or protect them against environmental factors [102]. This accumulation can also create a conducive microenvironment that supports the colonization and growth of larger plants, particularly in crevices or where substantial material accumulates, providing sufficient nutrients and anchorage. Over time, these conditions can lead to the growth of larger plant species, such as ivy and other woody plants, which may damage stone and mortar joints or block drainage systems in gutters [56,103,104].

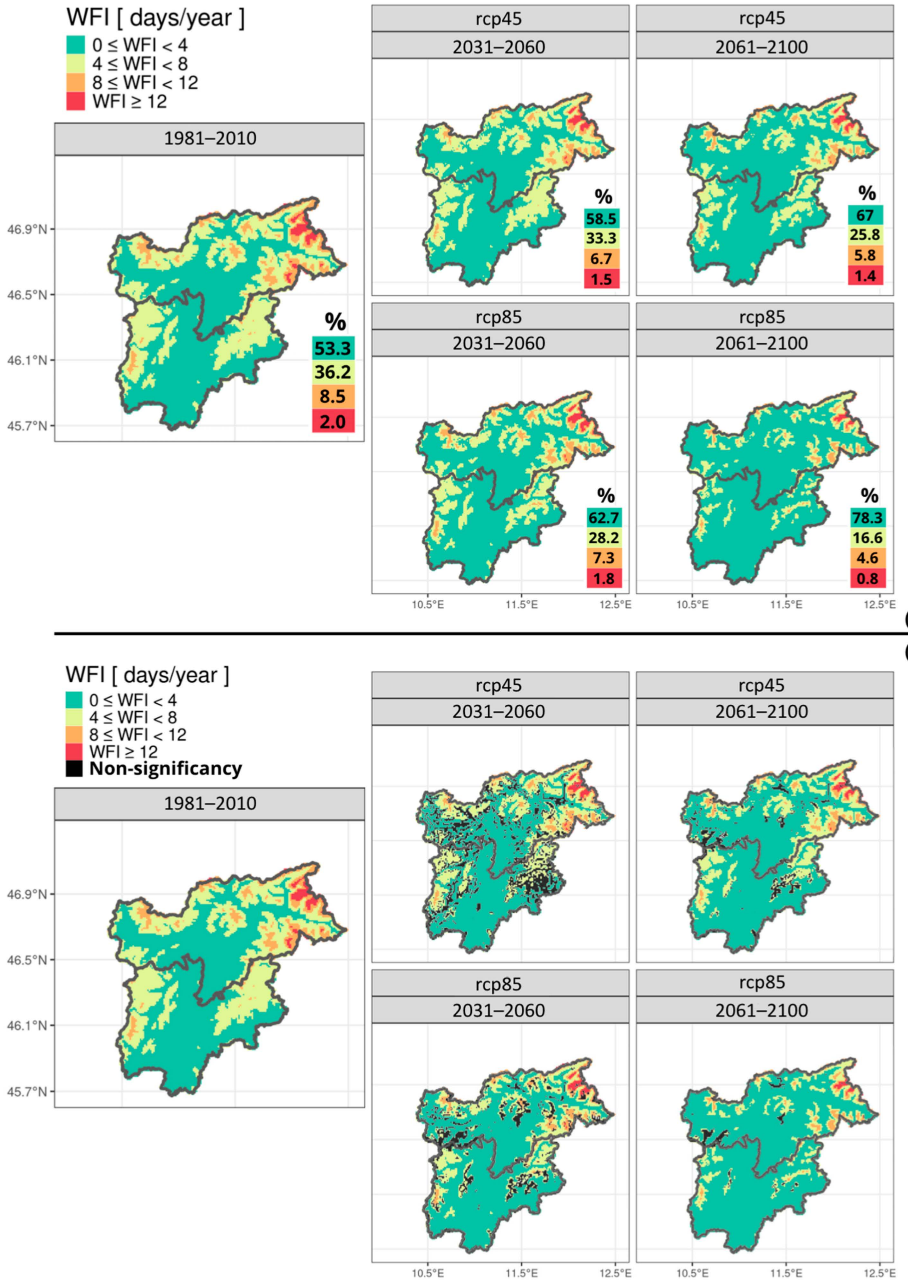

Figure 16. (**a**) Maps of climatological values of the risk in frost damages (wet-frost index) under the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios for three time periods: (**left**) 1981–2010, (**middle**) 2031–2060, and (**right**) 2071–2100. (**b**) Same maps as in (**a**) with black mask indicating areas with non-significant projected change relative to the baseline period 1981–2010.

As predicted by the research of Gomez-Bolea [102], B in the Alps shows minimal change, contrasting with the substantial decreases forecasted for Western and Southern Europe. Theoretically, in higher altitudes, temperature increases are accompanied by slight changes or increments in precipitation [102], potentially resulting in increased B. At lower latitudes, however, the anticipated effect is the opposite; the temperature increase is likely to be accompanied by a decrease in precipitation, negatively impacting biomass accumulation [102]. Figure 19 shows a general projected increase in biomass accumulation risk, in particular in the southern belt of the Province of Trento at high elevations and in a restricted area of the northern part of the Bolzano Province (see Figure 20a). This increase appears to be significant in the Far Future under RCP 4.5 and the Near Future under RCP 8.5 but seems to slow down abruptly in the Far Future under RCP 8.5 (see Table A2), possibly due to temperatures becoming too high for biomass to effectively colonize surfaces. Despite these findings, the uncertainty associated with projections for the Far Future is high (see Figure 19), and large portions of the region depict non-significant projected changes (see Figure 20b). However, beyond potential aesthetic change [13], the extent to which material deterioration or protection occurs due to increased biomass on surfaces remains undetermined [105].

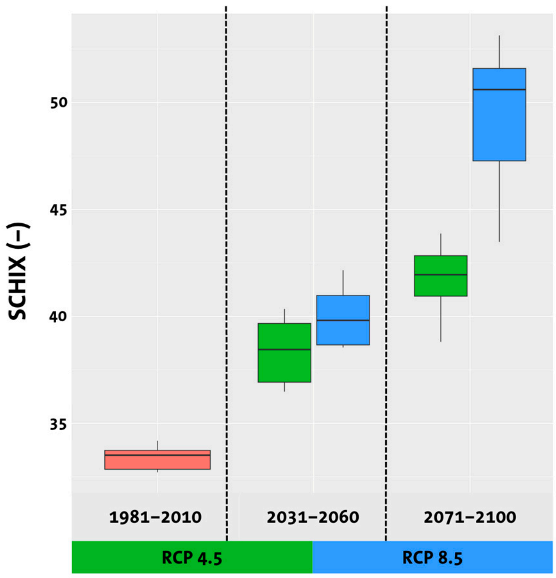

Figure 17. Boxplot of the regional average values of the Scheffer index (SCHIX), averaged over the three reference periods. Color fillings indicate historical simulation (red), projection under scenario RCP 4.5 (green) and projection under scenario RCP 8.5 (blue).

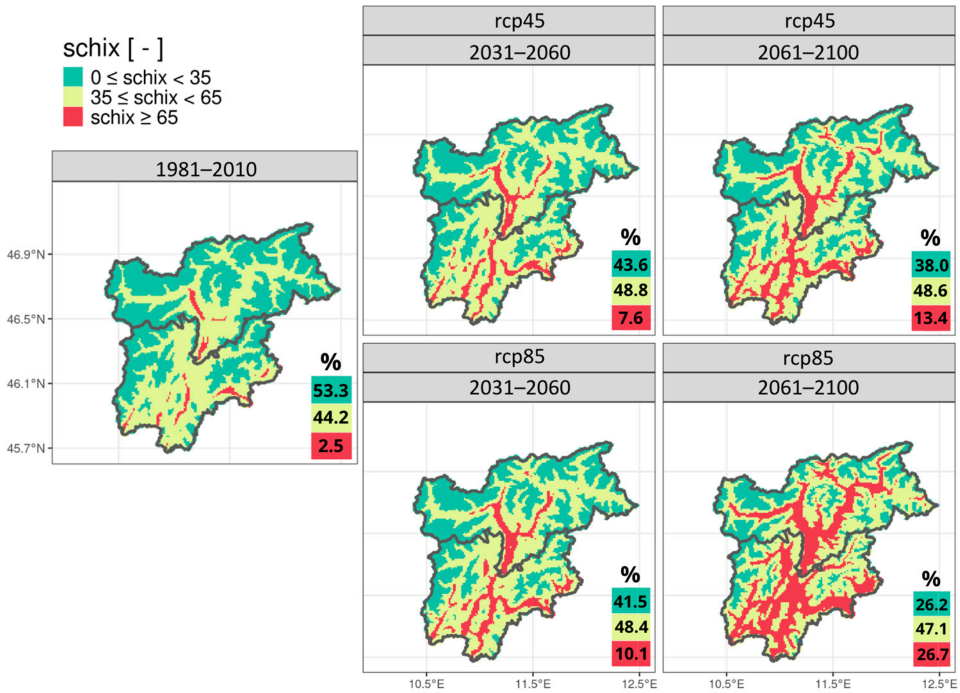

Figure 18. (**a**) Maps of climatological values of the risk in wood decay (Scheffer index with P = 0.2 mm) under the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios for three time periods: (**left**) 1981–2010, (**middle**) 2031–2060, and (**right**) 2071–2100.

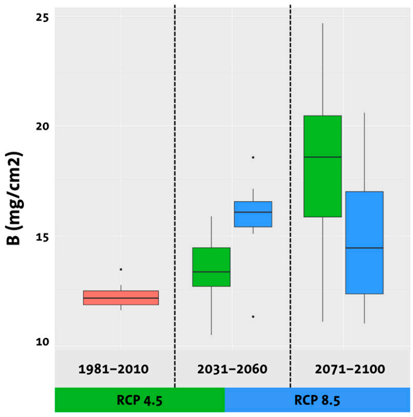

Figure 19. Boxplot of the regional average values of the biomass accumulation (B) index, averaged over the three reference periods. Color fillings indicate historical simulation (red), projection under scenario RCP 4.5 (green) and projection under scenario RCP 8.5 (blue).

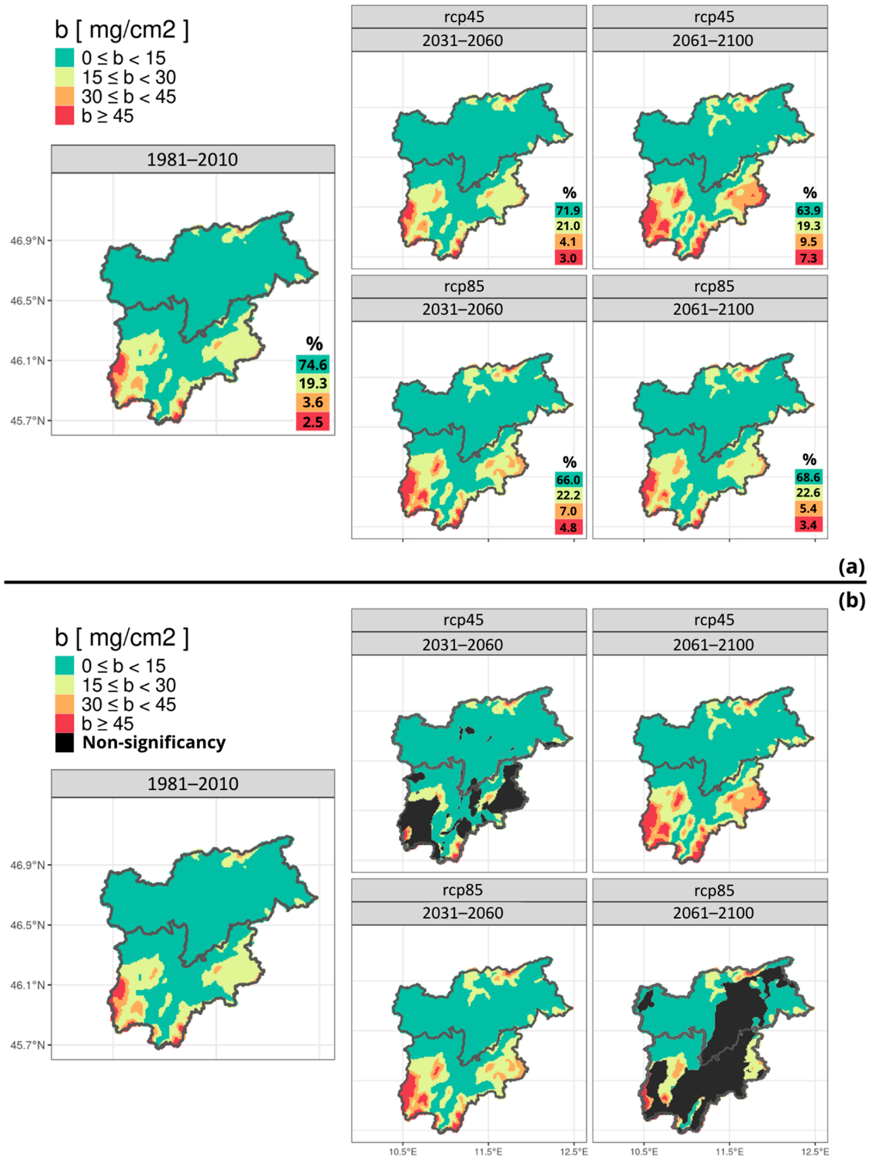

Figure 20. (**a**) Maps of climatological values of the biomass accumulation under the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios for three time periods: (**left**) 1981–2010, (**middle**) 2031–2060, and (**right**) 2071–2100. (**b**) Same maps as in (**a**) with black mask indicating areas with non-significant projected change relative to the baseline period 1981–2010.

4. Discussion and Proposed Adaptive

Understanding whether a phenomenon will increase or decrease in intensity and frequency is crucial for planning timely interventions or implementing preventive adaptive measures.

This study, along with the existing literature on adaptive solutions for historic buildings [6], proposes a structured approach for selecting region-specific solutions. Prioritization should consider regional hazards, cost–benefit analyses, and compatibility with heritage values. This approach can be summarized into a three-step decision-making framework: (i) Hazard Identification: check on climate-heritage hazard maps the dominant climatic hazards based on regional projections (e.g., heavy precipitation, biological decay); (ii) Solution Selection: empirically choose adaptive solutions tailored to mitigate the identified hazard (e.g., vegetation planting for temperature regulation); (iii) Cost Feasibility Analysis: perform a preliminary analysis of the cost-effectiveness of the selected solutions, considering factors such as implementation expenses, maintenance, and scalability for regional application. Note that this paper does not aim to conduct a market cost analysis of the proposed solutions, as their costs vary depending on site-specific applications.

For instance, D is projected to decline in valleys, particularly under high-emission scenarios, which extends this decline to the narrowest valleys and lower altitudes. This will likely reduce regional biodiversity and impact outdoor tangible heritage (e.g., archaeological sites, fountains, statues, and buildings) by altering their aesthetics and the protective or degrading role of lichens on building materials. One adaptive solution for mitigating the decline in lichen species involves planting vegetation to regulate air and stone surface temperatures and [15]. However, while vegetation offers health and thermal benefits, the cost of vegetation planting and its maintenance, along with the increased risk of insect proliferation and infestations (GDD), must be considered [106]. For FTCs, a decline, especially in valleys, is expected, reducing frost damage and consolidation needs. However, mountainous areas presenting temperatures persistently hovering on the freezing point necessitate targeted solutions, such as soft capping for horizontal stone surfaces [107,108], solid enclosures and vegetation caps for fountains [109,110], flexible enclosures for statues [109,110], shading shelters for archaeological sites [111], and protective coatings for stone surfaces [104,112]. Since the FTC threshold defined by Richards and Brimblecombe [72] and used in this paper lacks a material-specific assessment, this threshold must first be determined to improve solution efficacy. Among the two used, precipitation is the climate variable that has the highest uncertainty in future projections [44]. Therefore, indices related to precipitation have higher uncertainty than those related solely to temperature [72,96]. According to results on heavy precipitation indices, the Province of Bolzano is expected to see increases in both R10 and R20 over time and across various emission scenarios. Conversely, the southern part of Trento's Province is not expected to experience such an increase, as indicated by the anomaly maps (Figures 13 and 14), and may even see a slight decrease in these indices at the end of the century under RCP 8.5. The increase in heavy precipitation days raises the risk of water-related degradation processes, including salt crystallization, stone recession, mold growth, deep penetration, and glass lixiviation [113]. Solutions to these issues could involve applying specific coatings, enhancing roof and soil water drainage systems, and using double glazing to reduce lixiviation in stained glass windows [6]. The WFI seems to decrease across the entire region; however, the high uncertainty among the models makes interpretation challenging. If this value remains consistent at high altitudes, the suggested solutions are the same as those for FTCs. The SCHIX [48] is expected to increase, particularly in valleys, leading to greater risks of fungal wood decay. Applying specialized wood coatings can prevent moisture absorption and fungal growth. Finally, B is expected to increase overall, with some higher local peaks. These are not immediately concerning but may locally necessitate more frequent surface cleaning to prevent larger plants from taking root in this favourable microenvironment, which could potentially damage stone and mortar joints or obstruct drainage systems in gutters. The costs associated with regular maintenance versus installing preventative systems should be analyzed for heritage sites prone to biomass growth.

Thus, future conservation strategies for tangible heritage sites in Trentino–South Tyrol might not need to address frost damage or biomass accumulation. Instead, the focus should be on mitigating biological decay due to fungal and insect attacks, addressing material decay processes related to heavy precipitations, and combating the decline in lichen species. The latter is important as it signifies a broader decline in regional biodiversity.

Although this study shows quantitative data of evolving threats on a regional scale, making it possible for heritage decision-makers to prioritize conservation strategies in areas where risks are most significant, it is highly important to underline the major limitation of this study. For instance, the lack of benchmarks for most indices hinders the accurate assessment of risk to different materials. Currently, indeed, benchmarks exist only for the SCHIX, GDD15, and one definition of the FTC index. Since indices like freeze–thaw cycles can be defined in various ways, establishing common definitions would be crucial for facilitating comparisons across studies and creating reliable benchmarks. For insect-related indices, a more detailed study would be needed to identify the species present in the studied area and understand how each responds to temperature variations. For the SCHIX index, it is recommended to validate the results with field test data that reflect climatic differences on a finer spatial scale, such as in the case of Trentino–South Tyrol. Furthermore, there is a need to quantify the damage caused by variations in individual indices on different material types, which future experimental studies should aim to verify.

The limitations specific to this study include the restricted availability of bias-adjusted and downscaled climate data at the required resolution. Indices were selected among those based only on temperature and precipitation, since bias-adjustment and downscaling of these variables have already been performed in previous studies, although this choice limited the scope of the analysis. A more comprehensive regional assessment of the vulnerability of outdoor heritage materials would indeed benefit from incorporating additional climate variables, such as relative humidity and wind.

Additionally, the available temporal resolution was limited to one day, which constrained the use of indices that require hourly data. However, a significant advantage was the high spatial resolution of 1 km, which is particularly valuable in regions with complex orography, like Trentino–South Tyrol, where index values can vary considerably. Therefore, future studies on the region should incorporate these missing variables and utilize higher temporal resolutions. As for the proposed adaptive solutions, their actual effectiveness needs to be rigorously evaluated.

Moreover, the reliance of EURO-CORDEX simulations on RCP scenarios presents an additional limitation for the immediate use of the presented results in adaptation strategies, as these scenarios do not incorporate the socioeconomic narratives provided by the newer SSP-RCP framework, which are essential for assessing future vulnerability and adaptive capacity. However, the methodology presented in this study is designed to be transferable and can be applied to the next generation of EURO-CORDEX projections based on CMIP6 and SSPs, enhancing the robustness and policy relevance of future analyses.

Finally, to increase the practical relevance of these findings, this study emphasizes the importance of aligning the choice of adaptive solutions with the specific vulnerabilities, hazards, architectural materials, structures, plant species present, and microclimates of the heritage site [114]. Regional table-based cost estimations or rankings could further support decision-making processes for authorities and professionals. These latter could compare short-term solutions, e.g., protective coatings, with long-term structural solutions, e.g., new drainage systems, ensuring on one side the most economically sustainable with a cost-feasibility analysis, but also considering that all heritage values are preserved. Therefore, while these results provide a baseline for studying the necessary actions, it is highly recommended to bear in mind the potential variability of future outcomes and to remain adaptable to a range of possible scenarios [72].

5. Conclusions

This study examined future changes in a region by (i) projecting climate-heritage indices using regional climate models from the EURO-CORDEX ensemble, (ii) assessing the potential impacts on outdoor heritage materials of built heritage, and (iii) proposing adaptive solutions for the mitigation of climate impacts. Although applied to the Trentino–South Tyrol region, this methodology is intentionally designed for broad replicability across different geographical contexts. The versatility of the selected climate-heritage indices ensures that the methodology can be applied to a diverse range of heritage sites. Indices were calculated utilizing the open-sourced software climdex-kit, for the period 1971–2100 and for the RCP 4.5 and RCP 8.5 scenarios, with a high spatial resolution of 1 km, which is crucial for the region’s complex orography. Since the available high-resolution dataset was limited to precipitation and temperature data, the indices were selected based on their reliance on these parameters and their regional relevance. The chosen indices include the lichen species index, biomass accumulation, freeze–thaw cycles, growing degree days for insect activity, heavy precipitation days (R10 and R20), the Scheffer index, and the wet-frost index.

The results of the paper’s case study suggest a general increase in growing degree days, indicating heightened insect activity across the entire region. There is also a rise in the Scheffer Index, pointing to an increased potential for wood degradation, particularly under the RCP 8.5 scenario. Additionally, a localized increase in heavy precipitation days is projected, especially for the Province of Bolzano. Conversely, a decline in lichen growth, wet-frost events, and freeze–thaw cycles is expected, particularly in valley areas.

These findings offer essential insights into the future climate impacts on heritage buildings in the region, assisting heritage site managers in planning and designing targeted interventions. Indeed, the Knowledge Path, traditionally involving the acquisition of information from the structure’s past and present [115], should expand to include future considerations. This means incorporating detailed future risk analyses of climate indices, enabling us to proactively enhance building climate resilience and reduce the costs associated with continuous restoration interventions. This approach is closely related to the co-evolutionary approach, which suggests that historic buildings should be seen as living knowledge systems that interact with their environment over time, encouraging long-term thinking in restoration [116].

This shift toward future-oriented, site-specific planning is made possible by the methodological contribution of this study. In summary, compared to existing maps depicting this geographical area [11,32], this study provides higher resolution data, region-specific analysis, updated datasets, and a tailored set of adaptive solutions for the identified risks. This advancement results from the collaboration between climatologists and heritage practitioners. By adopting a multidisciplinary approach, this study emphasizes the importance of integrating scientific insights with practical expertise to develop actionable strategies that meet the region’s specific needs. Indeed, effective collaboration between these experts is crucial for helping heritage stakeholders develop and implement viable solutions to protect historic sites from climate risks [117].

Supplementary Materials: The following supporting information can be downloaded at: Code S1: file .ini.: https://gitlab.inf.unibz.it/earth_observation_public/cdr/climdex-kit/-/blob/usecase/st-heritage/src/climdex/etc/indices_camille.ini?ref_type=heads (accessed on 12 June 2025). Entire repository: https://gitlab.inf.unibz.it/earth_observation_public/cdr/climdex-kit/-/tree/usecase/st-heritage?ref_type=heads (accessed on 12 June 2025).

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Abbreviations

General	
D_n	Days with freezing events
D_{n+1}	Day after
D_{n-1}	Previous day
EURO-CORDEX	Europe Domain Co-Ordinated Regional Downscaling Experiment
ETCCDI	Expert Team on Climate Change Detection and Indices
GMC	Global Climate Model
RCP	Representative Concentration Path
RCM	Regional Climate Model
Indices	
B	Biomass Accumulation [mg/cm^2]
D	Lichen Species Richness [-]
FTC	Freeze–Thaw Cycle [days/year]
GDD15	Growing Degree Days with baseline value 15 °C [degree days/year]
R10	Heavy Precipitation Day with above 10 mm rain [days/year]
R20	Heavy Precipitation Day with above 20 mm rain [days/year]
SCHIX	Scheffer Index [-]
WFI	Wet-Frost Index [days/year]
Variables	
P	Daily Precipitation [mm]
P_y	Yearly Precipitation [mm]
$D_{pr,m,0.2}$	Monthly per month with over 0.2 mm of rain [-]
$T_{y,mean}$	Yearly mean temperature [°C]
$T_{m,mean}$	Monthly mean temperature [°C]
$T_{as,mean}$	Daily mean temperature [°C]
$T_{as,max}$	Daily maximum temperature [°C]
$T_{as,min}$	Daily minimum temperature [°C]

Appendix A

Table A1. Selected climate-heritage indices for the regional study on Trentino–South Tyrol.

Acronym	Name	Definition	Unity	Possible Change in Historical Building	Formula	Empirical	Existing Benchmark	Index Reference
Temperature-dependent indices								
D	Lichen species richness	N° of species per monument	-	Aesthetical change	$121.823–4.154 \times T_{y,mean}$	YES	NO	[13]
FTC	Freeze–thaw cycles	N° of days with maximum T over 0 °C and minimum below 0 °C	days/year	Mechanical deterioration	$T_{as,max} > 0$ °C and $T_{as,min} < 0$ °C	NO	NO (not for this definition)	[72]
GDD15	Growing annual degree-days	Growing annual degree-days, over 15 °C and below 30 °C for temperature-dependent insects	DD/year	Biological decay (insects)	$\sum_{jan}^{dec}(Tas, mean - 15)$	NO	Low Risk: 0–1000 Medium Risk: 1000–2000 High Risk: 2000–3000	[47]
Precipitation-dependent indices								
R10	Heavy precipitation days	N° of days per year with daily precipitation > 10 mm	days/year	Biological and Mechanical deterioration	$P > 10$ mm	NO	NO	[4]
R20	Heavy precipitation days	N° of days per year with daily precipitation > 20 mm	days/year	Biological and Mechanical deterioration	$P > 20$ mm	NO	NO	[13]
Temperature-Precipitation-dependent indices								
WFI	Wet frost index	N° of days in a year with >2 mm of rain and mean temperature > 0 °C followed immediately by days with mean temperature ≤−3 °C	days/year	Mechanical deterioration	D_n ($P > 2$ mm and $T_{as,mean} > 0$ °C) and D_{n+1} ($T_{as,min} \leq -3$ °C)	NO	NO	Author's Definition
SCHIX	Scheffer index	Increase of T_{mean} by rainy days with more than 0.2 mm of rain	-	Biodecay of wood (insect and fungal attacks)	$\sum_{jan}^{dec}([(Tm, mean\ - 2)(Dpr, m, 0.2 - 3)]/16,7)$	YES	Low Risk: SCHIX < 35 Medium Risk: 35 < SCHIX < 65 High Risk: SCHIX > 65	[98]
B	Biomass accumulation	Biomass accumulation on horizontal surfaces	mg/cm^2	Aesthetical change Biological and Mechanical deterioration Protection change from deterioration	$e^{(-0.964+(0.003Py-0.01Ty,mean)}$	YES	NO	[102]

Table A2. Quantitative values of Regional Climatology and Regional Relative Change, presented with the mean regional value and the range of values across the region [min; max] in brackets, for each index under RCP 4.5 and RCP 8.5 scenarios. Data are provided for the Reference Period (1981–2010), Near Future (2031–2060), and Far Future (2071–2100). The relative change is always referenced against the values from the Reference Period to highlight the projected changes across the region.

Acronym	Regional Climatology						Regional Relative Change [%]			
	RCP 4.5			RCP 8.5			RCP 4.5		RCP 8.5	
	Reference	Near Future	Far Future	Reference	Near Future	Far Future	Near Future	Far Future	Near Future	Far Future
D	104.3 [64.5; 162.5]	99.5 [59.4; 157.4]	96.4 [56.5; 154.1]	104.3 [64.5; 162.5]	97.8 [58.0; 155.6]	88.3 [48.8; 145.6]	−4.6 [−7.9; −3.1]	−7.6 [−12.4; −5.2]	−6.2 [−10.1; −4.3]	−15.3 [−24.3; −10.4]
FTC	143.7 [54.4; 209.9]	136.1 [29.2; 205.1]	128.4 [19.2; 208.6]	143.7 [54.5; 210.1]	131.8 [23.6; 208.1]	108.6 [3.5; 205.1]	−5.3 [−46.3; −2.3]	−10.7 [−64.7; −0.6]	−8.3 [−56.7; −1.0]	−24.4 [−93.6; −2.4]
GDD15	140.8 [0; 1045.7]	209.9 [0; 1218.8]	239.3 [0; 1300.8]	140.7 [0; 1045.0]	218.6 [0; 1265.9]	377.5 [0; 1425.2]	+49.1 [0.0; +16.6]	+70.0 [0.0; +24.4]	+55.4 [0.0; +21.1]	+168.3 [0.0; +36.4]
R10	32.4 [14.2; 50.6]	33.3 [15.6; 50.1]	34.3 [15.8; 52.1]	32.5 [14.3; 50.7]	34.6 [15.9; 52.3]	34.0 [16.1; 49.0]	+2.8 [+9.9; −1.0]	+5.9 [+11.3; +3.0]	+6.5 [+11.2; +3.2]	+4.6 [+12.6; −3.4]
R20	12.7 [4.0; 28.0]	13.3 [4.4; 27.6]	14.0 [4.7; 29.5]	12.7 [4.0; 28.0]	14.2 [4.8; 29.6]	14.1 [4.9; 27.5]	+4.7 [+10.0; −1.4]	+10.2 [+17.5; +5.4]	+11.8 [+20.0; +5.7]	+11.0 [+22.5; −1.8]
WFI	4.3 [0.3; 19.0]	3.9 [0.1; 18.2]	3.4 [0.0; 19.0]	4.3 [0.3; 19.4]	3.7 [0.1; 18.6]	2.6 [0.0; 16.1]	−9.3 [−66.7; −4.2]	−20.9 [−100.0; 0.0]	−14.0 [−66.7; −4.12]	−39.5 [−100.0; −17.0]
SCHIX	32.9 [0.1; 77.8]	38.1 [0.1; 84.4]	41.5 [0.1; 89.7]	33.1 [0.1; 78.5]	39.6 [0.1; 86.5]	49.8 [1.1; 86.5]	+15.8 [0.0; +8.5]	+26.1 [0.0; +15.3]	+19.6 [0.0; +10.2]	+50.45 [+1000.0;+10.9]
B	12.2 [1.8; 90.3]	13.4 [1.9; 100.5]	18.2 [2.0; 225.5]	12.3 [1.8; 102.1]	16.0 [2.0; 118.9]	14.4 [1.9; 104.8]	+9.8 [+5.6; +11.3]	+49.2 [+11.1; +149.7]	+30.1 [+11.1; +16.5]	+17.1 [+5.6; +2.6]

Table A3. Results of the indices' projections, consequences of the indices' variations in the region, and suggested adaptive solutions.

Indices	Results	Consequencies	Solutions
Lichen Species Richness (D)	General decrease in valleys; Far Future (RCP 4.5): decrease reaches also narrow valleys; Far Future (RCP 8.5): decrease affects also small altitudes.	Decrease of biodiversity; Change in aesthetics; Change in degradation/protection role of lichens	Planting Vegetation
Growing Degree Days (GDD)	Increase in valleys	Increase in wood attacking insects	Removal of close trees
Freeze–Thawing Cycles (FTC)	Decrease in valleys	Decrease in frost damages	Soft capping for horizontal stone surfaces; Vegetation capping for fountains; Solid Enclosings for fountains; Flexible enclosings for statues; Shading shelters for archaeological sites.
Heavy Precipitation Days 1 (R10)	General increase	Increase in biological and mechanical deterioration e.g., deep penetration, salt crystallization, mould, stone recession, etc.	Roof and soil drainage system redesign and maintenance; Façade detail augmentation or adding; Installation of rodding point, wire balloons, grille-covered gulley traps and french drains; Application of waterproofing coatings; Installation of EPGs.
Heavy Precipitation Days 2 (R20)	General increase	Increase in biological and mechanical deterioration e.g., deep penetration, salt crystallization, mould, stone recession, etc.	Same as in R10
Wet-Frost Index (WTI)	Small general decrease, with high uncertainties	Small decrease in frost damages	Same as in FTC
Scheffer Index (SCHIX)	General high increase; Shift from least favourable-intermediate to intermediate-most favourable conductive condition for wood decay.	Increase of decay hazard induced by wood-degrading fungi on wooden elements.	Specialised coatings; Avoid humidity/water absorbtion.
Biomass Accumulation (B)	General increase	Change in aesthetics; Change in biochemical role of biomass.	Cleaning of surfaces; Specialised coatings.

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