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Köppen climates and Scheffer index as indicators of timber risk in Europe (1901–2020)

Peter Brimblecombe¹ and Jenny Richards^{2,3*}

Abstract

Timber heritage faces numerous risks, with the threat from insect and fungal attack particularly sensitive to climate. The Scheffer index estimates the deterioration of wood by combining average temperature and days of rain. We determined the Scheffer index from twenty sites in Europe across the 20th and early 21st century using meteorological observations, largely from the European Climate Assessment Dataset. Results showed that Scheffer indices across Europe loosely align with Köppen climate classes, which are also defined in terms of temperature and rainfall. However, within a given Köppen class, a wide range of Scheffer indices were found, thus representing very different threats to heritage. This suggests that specific heritage climate parameters, such as the Scheffer index, are needed. Trends in the Scheffer index provide a fairly robust guide to management strategy by identifying locations where the risk for timber is increasing. However, a simple index cannot necessarily describe the complex interactions between biological pests and climate; such complexity is better handled with well-constructed models. Nevertheless, the Scheffer index offers heritage managers an easily calculated estimate of the spatial distribution of risk to timber and the likely direction of future change.

Keywords Built heritage, Heritage climatology, Long term exposure, Climate change, Climate projections

Introduction

The long-term exposure of heritage materials to the environment can lead to their deterioration with a changing climate of special concern [1, 2]. Understanding the history of risk is important in managing our heritage [3]. As timber is a common building material across much of Europe, it is important to assess its conservation needs [4]. It is a highly versatile material, being used for example to form structural elements in buildings, decorative carvings, indoor furniture and instruments [5]. We focus

on timber heritage exposed to external conditions as this material is sensitive to weather and climate. Wood faces multiple risks from relative humidity range, seasonality of relative humidity, time of wetness, wind-driven rain, salt transitions and biological attack [6–8], as well as risks from extreme events such as fire [9, 10], flooding and landslides [11]. While damage from extreme events can be catastrophic, the effect of less extreme conditions can cumulatively result in a substantial risk to heritage that requires ongoing management.

Timber architecture in Europe includes, for example, notable agricultural buildings, such as the medieval Great Barn in Harmondsworth, UK [12]; timber framed (*Holzfachwerk*) structures that are most characteristic of Germany, but are found throughout much of Europe [13]; and stave churches across Scandinavia [14].

Assessment of the weathering risk requires an understanding of climate. Spatially, this has often been

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described in terms of temperature and precipitation, as seen in the Köppen system of classification [15]. The classes are regularly used to describe ecosystems but have been adopted to describe the climates of heritage sites and landscapes [16, 17]. However, the Köppen approach fails to include many important parameters relevant to heritage damage, such as humidity or wind [18].

The Scheffer index provides a measure of potential decay in timber structures [19]. It uses both temperature and rain as inputs and so would seem likely to be a heritage damage parameter that could align with the Köppen classification. Due to the rainfall parameter in the Scheffer index, this index is applicable to timber exposed to outdoor conditions. It has previously been used to assess the risk of timber deterioration at national (e.g., Japan [20], Korea [21, 22], Norway [23], Switzerland [24], the UK [25] and the USA [26]), regional [1] and global scales [6, 7]. Index thresholds, for low–medium (35) and medium–high risks (65) have been assigned, but as these were originally tuned to the continental US, transferring it to different regions may require recalibration [27]. Daily records of temperature and rainfall are required to calculate the Scheffer index [28]. Europe has many series of daily records [29], with some being particularly lengthy [30–32]. For example, the Kew rainfall record and Central England Temperature Record (CETR) can be combined to give a rough estimate of Scheffer back to the early 18th century. However, not all these datasets are readily accessible or usable.

Here our aim is to determine the long-term record of the Scheffer index for Europe, and we focus most attention on the period 1901/2020 (dates here follow ISO 8601). This has not previously been attempted for Europe using long term observational data, but examining the continent as a whole allows a broad comparison between countries. We also wish to explore whether Köppen classes are associated with the spatial patterns and trends in the Scheffer index, and assess their agreement with output from global models. This study should contribute to the strategic management of timber heritage, by suggesting regions that have experienced notable changes and those that might be at greater risk in the future.

Methods

Scheffer index

The Scheffer index [19] estimates the risk of timber decay, as expressed in the equation: $Sch = \sum [(T_m - 2)(D_m - 3)]/16.7$, which represents the sum over twelve months of the products of the monthly mean temperature (T_m) and number of days in the month with ≥ 0.3 mm of rain (D_m). However, as rain days with ≥ 0.2 mm of rain are more typically seen as rain

days [<https://glossary.ametsoc.org/>], we have used this definition here.

The Scheffer index has also been split into its temperature and rainfall components using the following equations:

$$T_{Sch} = \sum (T_m - 2)/16.7$$

$$D_{Sch} = \sum (D_m - 3)/16.7$$

noting that the divisor 16.7 is simply used to retain the conventional form of the Scheffer equation.

Observational data

This study uses existing records of temperature and rainfall across a range of European climates. We retrieved daily observations retrieved from online datasets. We drew from records collated by the European Climate Assessment Dataset project (ECA), which provides 84 967 series of observations for 13 elements at 22 841 meteorological stations throughout Europe and the Mediterranean [29]:

<https://www.ecad.eu/dailydata/predefinedseries.php>.

Additionally, we used a number of long-term records from the UK, notably those from the Radcliffe Observatory in Oxford [33] and the Durham Observatory [34]:

<https://www.geog.ox.ac.uk/research/climate/rms/daily-data.html>.

<https://durhamweather.webspace.durham.ac.uk/open-access-climate-datasets/>.

and accessed the record from the Austrian sites downloaded for Vienna (Hohewarte) and Kremsmünster from the ZAG site [35]:

<https://data.hub.zamg.ac.at>.

the record from the Praha-Klementinum [36].

<https://www.chmi.cz/historicka-data/pocasi/praha-klementinum?l=en#>.

and data for Oslo from two separate sites (Oslo—Observatoriet, Hytte and Blindern) [37]:

<https://seklima.met.no/stations/>.

Apart from the Oslo datasets the observations are available from the EAC, but the records from local observatories were sometimes useful in establishing details of site changes and concerns with the homogeneity of the records (e.g. [33, 34]).

Sites

Sites chosen for this study had weather records extending back to at least the beginning of the 20th Century, but some began in the 18th Century (Table 1). In addition, to cover a range of Köppen climate types, we selected sites

Table 1 Sites used in this study

| Code | Site | Country | Köppen class | Begins | References |
|------|----------------------|----------|--------------|--------|------------|
| Aach | Aachen | Germany | Cfb | 1891 | [29] |
| Arxa | Arxangel'sk | Russia | Dfc | 1881 | [29] |
| Durh | Durham | UK | Cfb | 1880 | [34] |
| Giro | Girona | Spain | Csa | 1896 | [29] |
| Grei | Greifswald | Germany | Dfb | 1890 | [29] |
| Hapa | Haparanda | Sweden | Dfc | 1859 | [29] |
| Hvar | Hvar | Croatia | Csa | 1858 | [29] |
| Jokk | Jokkmokk | Sweden | Dfc | 1871 | [29] |
| Kare | Karesuando | Sweden | Dfc | 1878 | [29] |
| Kiev | Kiev, Kyiv | Ukraine | Dfb | 1900 | [29] |
| Krem | Kremsmünster | Austria | Dfb | 1874 | [29] |
| Ljub | Ljubljana | Slovenia | Dfb | 1900 | [29] |
| Mars | Marseille | France | Csa | 1900 | [29] |
| Mila | Milan | Italy | Cfa | 1858 | [29] |
| Oslo | Oslo | Norway | Dfb | 1877 | [37] |
| Oxfo | Oxford | UK | Cfb | 1815* | [28] |
| Prag | Prague | Czechia | Dfb | 1804 | [29, 36] |
| Shen | Shenkursk | Russia | Dfc | 1884 | [29] |
| Stoc | Stockholm | Sweden | Dfb | 1859 | [29] |
| StPe | St Petersburg | Russia | Dfb | 1881 | [29] |
| Vien | Hohewarte, Vienna | Austria | Dfb | 1852 | [29] |

Oxford date extends into the 18th century and as daily values from 1815, but changes in instrument locations means that we have only used observations from the 1850s. In this study, sites are referred to by anglicised versions of their names and some cities names and/or spellings have changed across the study period, most recently Kiev to Kyiv as tabulated

distributed across the major Köppen classes in Europe. The class are distinguished by their three-letter classifications: (i) Dfc cold norther climates, typically at high latitude, that are cold with no dry season; (ii) Dfb, continental climates, that are cooler with no dry season and warm summers; (iii) Cfb, western European maritime climates that are temperate with no dry season and warm summers and Cfa and Csa temperate climes mostly on the northern Mediterranean fringes with hot summers with dry weather (Fig. 1). The climate types have been grouped to clarify the European context important to this study as: Dfc—boreal, Dfb—continental, Cfa and Csa—Mediterranean and Cfb—Atlantic.

As the project is concerned with built heritage, it was important to choose cities or areas with substantial settlements, which could represent a stock of historic timber buildings. For example, there are historic timber churches in Oslo and St. Petersburg; timber framed houses in many cities including Vienna, Oxford, and Marseille and the sites also include World Heritage historic city centres, such as Prague. The coverage of our datasets is not evenly spread, with notable gaps in Belgium, France and northern Spain, where long records

were absent from the database, resulting in Köppen Cfb climates being represented only by Aachen, Durham and Oxford. Furthermore, we were only able to capture the northern margins of the Mediterranean, as we could not access longer records from Greece, Malta or southern Italy, and the east of Europe is represented only by Ukraine and Croatia, despite a wealth of heritage in this region. The coverage of the central and northern areas of Europe is strong, which was an advantage given the richness of timber heritage in these regions [39].

Figure 1b shows the mean annual Scheffer index across the years 1984/2013 as derived from a global study of moisture as a driver of long-term threats to timber heritage [7]. The colours representing the Scheffer index are different to those in the figure of Richards and Brimblecombe [7] to amplify the range of Scheffer index values across Europe. Figure 1b reveals a broad trend of higher Scheffer indices in the maritime west of Europe that slowly decline to the east. The Mediterranean and boreal climates also show lower values. This map suggests a distribution somewhat different to that of the Köppen climates displayed in Fig. 1a; noting especially the band of low Scheffer indices stretching from Spain into Southern France, absent from the Köppen map. Additionally, it is clear from the figure, that indices are low at high latitudes, especially Norway and Sweden, but to some extent also the Russian Arctic, where many months are below 2 °C so make no contribution to the index. The Scheffer index is high in the wetter climates of the low countries and the British Isles.

Statistical analysis

The meteorological data in this study frequently reveal a non-normal distribution. We have often adopted box-and-whisker plots to present the central tendency and range. The boxes represent the lower and upper quartiles (Q_1 and Q_3), with the median (\tilde{x}) denoted by the central line in the box and a cross to represent the arithmetic mean (\bar{x}). The whiskers show the range of all other points, except those that are deemed as outliers. An outlier is considered to be any value that lies over 1.5 times the range below and above Q_1 and Q_3 . The Kendall τ statistic was used for express rank correlation in bivariate data sets. We used the non-parametric Mann–Whitney test, rather than the t-test, to assess significant differences in sets of results from time periods. The Friedman test was used rather than the correlated ANOVA to compare 30-year blocks or data from multiple sites.

Results and discussion

Scheffer indices in Europe

The mean Scheffer indices for the period 1991/2020 (the most recent 30-year climate normal) calculated from

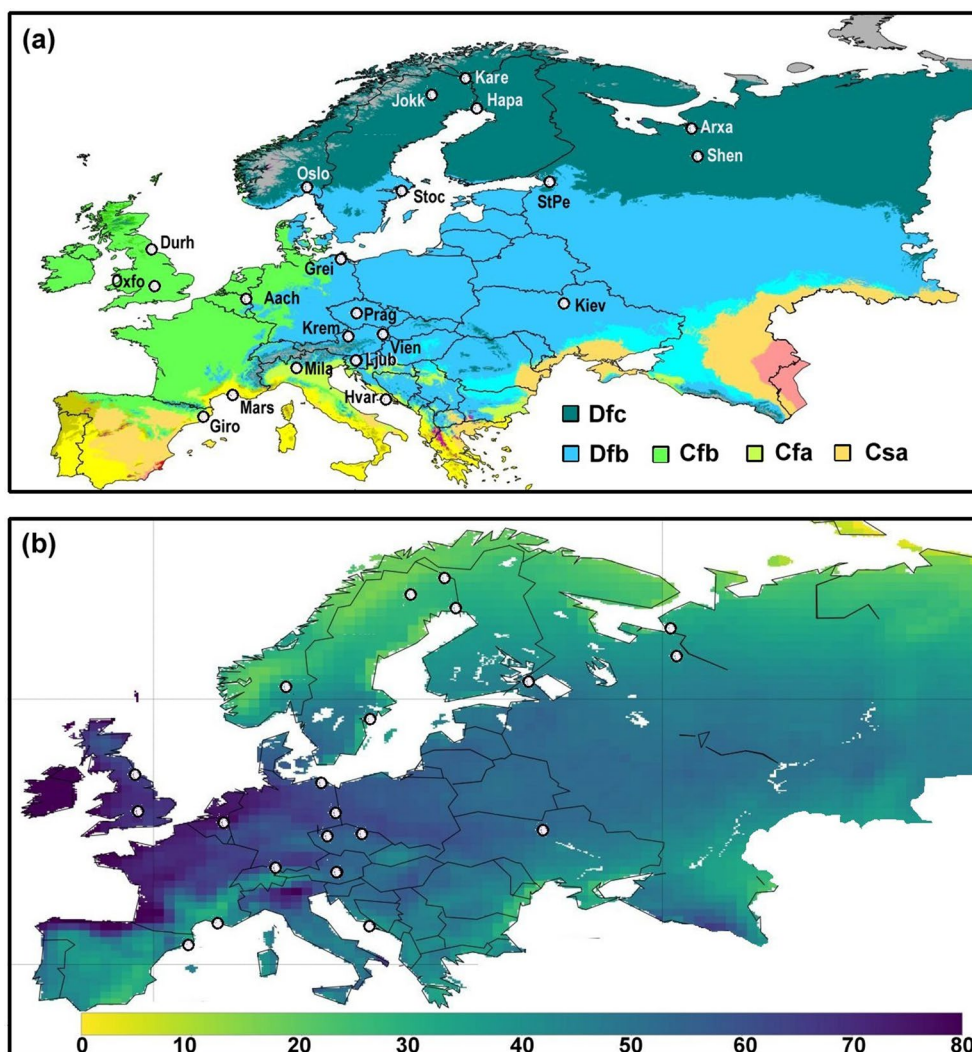


Fig. 1 **a** Observational sites used in this study, plotted on a map of the Köppen climate classes of Europe (1980/2016) [38]. See Table 1 for site abbreviations. **b** Map showing modelled Scheffer indices from the period 1884/2013 [7]

the long-term records vary across Europe, from 24.4 at Karesuando, Sweden, to 68.7 at Aachen, Germany. Figure 2 shows that those calculated from observed values agree (Kendall $\tau=0.7$; $p<0.0001$) with predicted Scheffer indices for the period 1984/2013 as mapped in Fig. 1b from earlier modelled output [7]. This suggests that the observations largely follow the spatial trend of the Scheffer indices suggested in the map derived from the HADGEM-GC31-MM CMIP6 output.

Figure 2 also suggests that sites from different Köppen classes cluster together implying a fair agreement between the Köppen climates and the calculated Scheffer indices, previously alluded to in the comparison of Fig. 1a, b. However, individual values of two sites of the same Köppen class can vary markedly. For example, both

Stockholm and Kremsmünster are classed as having continental climates, yet they have observed Scheffer indices of 41.5 and 68.7, respectively (Fig. 2). This suggests that the continuous nature of the Scheffer index, compared to the categorical nature of the Köppen classes, enables the Scheffer index to be more sensitive to climate pressures on timber by operating over a spectrum of values rather than via discrete classifications.

Past change in Scheffer indices

The Scheffer indices for the four periods of the climate normals 1901/1930, 1931/1969, 1961/1990 and 1991/2020 are shown for all sites in Fig. 3. The boreal climates (Dfc) have low Scheffer indices, with the continental climates; cold winters, but warmer summers (Dfb)

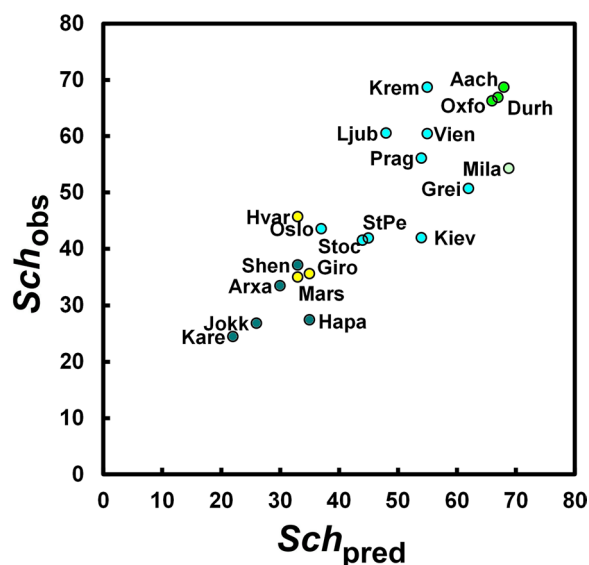


Fig. 2 The calculated Scheffer indices as a function of the mean from each site for the period 1991/2020 derived from the mapped data for the predictions (1984/2013) as shown in Fig. 1b

exhibiting higher Scheffer indices. The highest values are found in the temperate climates with warm summers (Cfb) and with the dry Mediterranean climates showing lower values.

Again, the results in Fig. 3 give a general impression that the Köppen classes are descriptive of the Scheffer index, but again do not capture the large variability that can occur within a Köppen class. For example, a Kruskal-Wallis Test on the five boreal (Dfc) sites for the most recent period shows that the sites are not all the same ($p < 0.0001$) and range from a median integer value of 24 at Karesuando to 37 at Shenkursk. There is also significant difference within the continental (Dfb) sites

that range from Stockholm 42 to Vienna 61. The Atlantic (Cfb) sites occupy a narrower range (Aachen 69; Oxford 66) and the Mediterranean sites exhibit a wide range, although lower (Milan 54; Marseille 35).

For the sites in the cold boreal climates and continental climates with warm summers (Dfb), the Scheffer index increases over time (Fig. 3). In the case of the boreal climates the Friedman test suggested the four 30-year periods gave mean ranks of 2.60, 1.60, 2.60 and 3.60, suggesting that the most recent period was the highest; differences between the periods significant at $p = 0.013$. The same was true of the continental climates with warm summers (Dfb) giving mean ranks as 1.9, 2.3, 2.3 and 3.9 ($p = 0.01$). The statistics were not as reliable for the Atlantic climates (Cfb) as there were only three sites and these gave the ranks as 1.3, 3.3, 1.5 and 3.7, with lower statistical significance ($p = 0.063$). In contrast the drier climates in the Mediterranean showed little evidence of an increase over time, with mean ranks at 3, 2, 2 and 3 a non-significant ($p = 0.39$) difference between the 30-year periods.

It is possible to use longer climate records from a few sites with 19th century observations, and these reinforced the changes seen 1901/2020. Across the 30-year period 1871/1900 in Haparanda, the median Scheffer index was only 12.1 reflecting very cold conditions in the late 19th century, compared with 26.2 for the 30-year normal 1991/2020. The values are lower for the other site, although nowhere near as dramatic comparing 1871/1900 with 1991/2020 for: Prague 47.8 and 58.6; Vienna 55.7 and 60.6; Durham 52.2 and 68.5; Oxford 51.5 and 68.0; Hvar 39.8 and 43.8. The differences are all significant ($p_2 < 0.05$) using a Mann-Whitney test, except for Hvar, where the index appears to be in decline overall (Fig. 3), reinforcing the low level of change for Mediterranean climates noted in the previous paragraph.

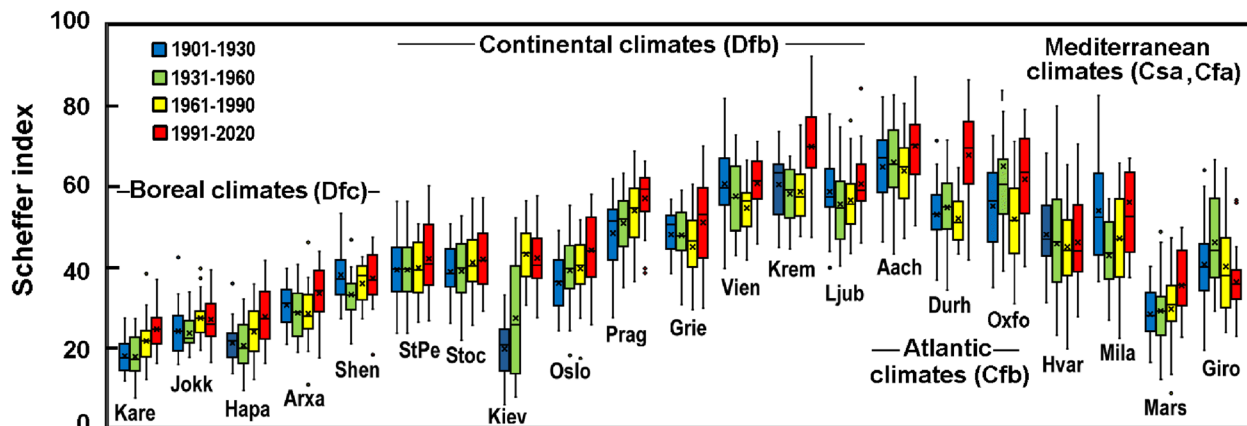


Fig. 3 Box-and-whisker plots of the Scheffer index for the four 30-year climate normal periods starting from 1901 at the sites used in this study

Temperature and rain components

The formula for the Scheffer index has two multipliers, that which includes average temperature (T_{Sch}) and the number of rain days (D_{Sch}), as described in the [method](#) section. Figure 4 shows the average contributions from T_{Sch} and D_{Sch} over the four climate normal periods.

Our results show the Scheffer indices in boreal climates of Northern Europe (Dfc) gain a relatively small contribution from temperature and a wide range of contributions from days of rain (Fig. 4). By contrast the warmer drier climates of the Mediterranean (Csa) show a strong influence from temperature, but relatively little from rainfall. The damp Atlantic climates of Western Europe (Cfb) are more temperate so show a mild temperature influence, along with a strong effect from rainfall. The continental climates (Dfb) have less effect from rain, but their summers can be warm, while those in the Baltic (St. Petersburg and Stockholm) not surprisingly lie close to the area of the graph occupied by the boreal climates.

Figure 4 also shows the change in the relative contribution of T_{Sch} and D_{Sch} over time. The arrows in Fig. 4 reflect the direction of movement underway in the data across the four 30-year periods, as derived from the median shifts in the temperature and rainfall components the sites within a Köppen class. In boreal regions (Dfc) and the damper Atlantic climates of Western Europe (Cfb) there is a tendency for an increase in both rain days and temperature contributions, hence the sense of the changes that are likely to be seen in Northern Europe, that was represented in the bar charts of Fig. 3. The change driven by rainfall is important more generally

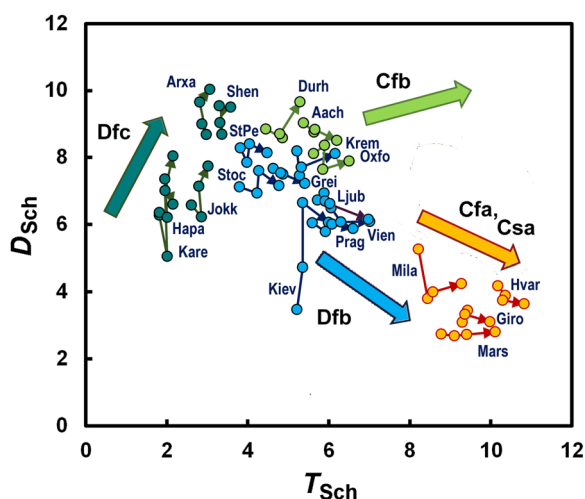


Fig. 4 The comparative influence of the rain days (D_{Sch}) and temperature (T_{Sch}) components of the Scheffer index for the four climate normal periods at each site. The large arrows represent the median shift in the temperature and rainfall components of the Scheffer index for all values within a given Köppen class

for regions poleward of 60°, as earlier work showed that large increases in the Scheffer index in future would typically be caused by increased rainfall at high latitudes [7]. The changes in both T_{Sch} and D_{Sch} are also positive for the damper Atlantic (Cfb) climates and are imposed in areas where Scheffer indices are already high (Fig. 3).

In the other two climate groups (Dfb; Csa-Cfa) temperature contributions have strengthened over time, while the rain day influence has fallen (Fig. 4). Therefore, the opposing tendencies in the two factors that contribute to the Scheffer index may explain why change seems small in the Mediterranean climates (Csa). More specifically we can see some interesting characteristics among individual locations such as Stockholm and St. Petersburg, which seem rather like the Boreal Dfc climates from their position on the figure. However, they are likely to move towards higher temperatures, rather than exhibit an increasing importance of the rain day component noted for the cold climates, thus these Baltic sites seem quite distinctive.

Longer term changes

An earlier global analysis that modelled the changes expected over a century and a half (1850/2099) suggested that latitude zones 0–30° N/S would often see large increases in the Scheffer index (up to 50) with temperature as the main driver of change over the 21st century [7]. Poleward of 60°, increases in the Scheffer index were projected to be caused by increases in rain days. However, for areas where there have been smaller increases, or reductions in the Scheffer Index, it is likely to be changes in rainfall that are driving the change [7]. The projected change in the Scheffer index across from 1850/1879 to 2070/2099 as seen in earlier work [7] is similar to the overall observations one might make from Fig. 4. Change is notable in the boreal climates, where both rainfall and temperature increases seem likely to increase the index, albeit from modest values. Further south there is a balance between a decreasing effect from the rain component and an increase in the temperature component.

Management implications of risk

Figure 5 compares the change in the Scheffer index, as shown as the median rate of change over the last 120 years (i.e. a Theil-Sen slope), with the level of risk. Our results show that the majority of sites are at medium risk, with one site (Aachen) at high risk and five sites at low risk (Fig. 5).

In the Mediterranean (i.e. Hvar, Milan and Girona) the Scheffer index has decreased, although there is considerable error in assigning these slopes. The correlations across the 120-year periods had p -values 0.30, 0.33 and 0.012 respectively, so only Girona was significant.

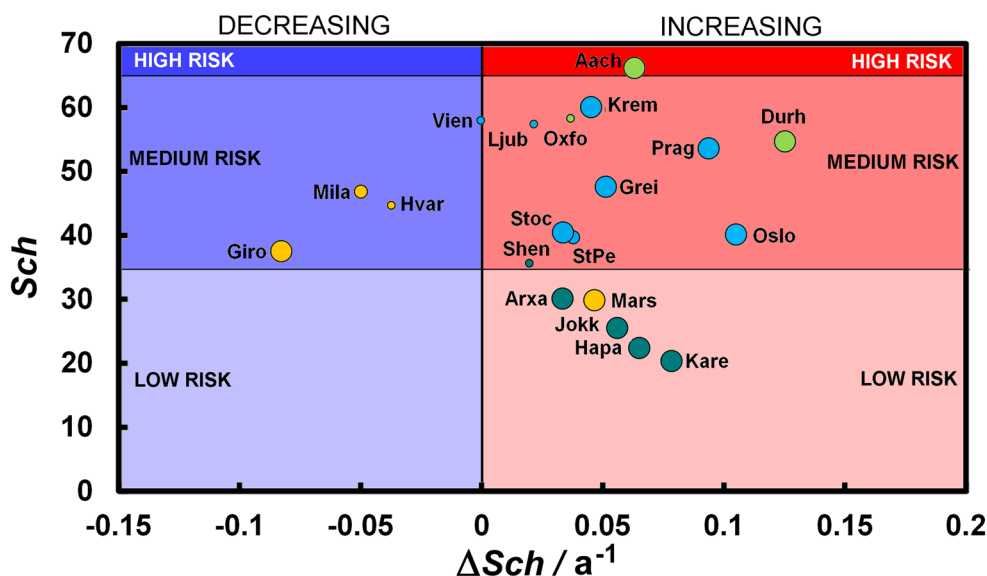


Fig. 5 Median values of the Scheffer index 1901/2020 at the sites as a function of its rate of change per annum (Sen slope). Colours of the points follow the Köppen classes as in Fig. 1. Symbol sizes are small to large; $p > 0.2$, $p 0.1-0.2$ and $p < 0.1$ indicating the significance of the slope. Site abbreviations and number of years in each record are as in Table 1

These Mediterranean sites seem to be moving towards climates that are less risky for timber. Most other areas show modest increases although at the boreal sites and Marseilles this is from a rather low base, and so the overall risk remains low. In general, it looks to be the continental sites and the sites in the west of Europe, mostly at medium risk, that reveal increasing Scheffer indices.

The direction of change is obviously of importance to management as a decrease in the Scheffer index would suggest a lowered need for additional conservation effort. The direction of changes in risk is likely to be imposed on both new wood with a high water content and old wood, that is dry, although the impact of such threats may vary. It may be important in management strategies to appreciate locations with rapid change and perhaps places where the Scheffer index is likely to move to new risk categories. In many cases, it is change that leads to conditions that are unfamiliar which may be critical to heritage management. This could mean that there is difference between the balance of threats to buildings in the past, compared to those likely in the future. Thus, the change in Scheffer index can be interpreted in terms of management options when considered as the likely risk (Fig. 6). We can see that the proportion of times where there is a higher risk for timber increases from the past (1901/1990) to the most recent period (1991/2020).

The boreal (Dfc- Northern Sweden and Russia) and Baltic climates (Stockholm and St Petersburg) show little change in the distribution of risk (Fig. 6). Although warmer climates may cause the risk to grow, it has remained rather modest and overall low. This is likely to

be especially important given the relevance of wooden architecture, such as stave churches in these regions. This means that managers would be able to focus on a range of other drivers of damage to consider under a changing climate, such as temperature and relative humidity cycles [40, 41].

A parallel situation pertains to the drier climate (Csa) of Mediterranean Europe where there seems little change to the risks imposed on wood, although these sites remain vulnerable to fire and other risks. Nevertheless, the more temperate regions appear to have experienced potentially enhanced risks to timber from increasing proportions of the years in the higher Scheffer risk categories. Except for Kyiv (formerly Kiev), the sites with continental climates (Prague, Greifswald, Kremsmünster and Vienna) all show occasional years with high risk. Given the wealth of timber heritage in these regions it will mean that sites which experience a deterioration of timber are likely to see continued risk, so may become an element of management plans. A year with high risk may especially be relevant to heritage management, so conservation professionals might need to be aware of the potential that enhanced risk to timber may not involve long term means, but possibly the frequencies of years with anomalously high Scheffer indices. However, the occurrence of these high-risk years has not been explored in this paper.

The broader threat to timber in Western Europe parallels the risks from fungal attack that has long been of concern in damp historic buildings [42]; a threat likely to grow in future [43]. There are a range of indirect effects to consider along with the complex interactions between

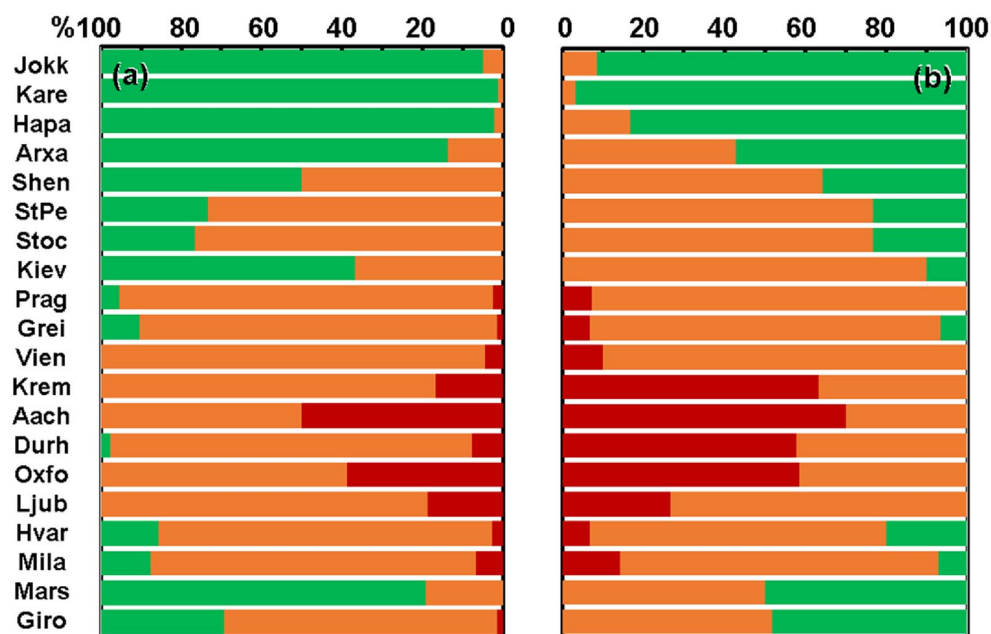


Fig. 6 The Scheffer risks: low (<35 green), medium (35–65 orange) and high (>65 red) for the periods **a** 1901/1990 and **b** 1991/2020 at the sites (abbreviations as in Table 1)

fungi and insects. Eggs of the deathwatch beetle (*Xestobium rufovillosum*) are often laid on wood that has previously been degraded by fungi wood as their larvae prefer softened wood [44]. Under the changing climate conditions described in this paper, it is likely that biological interactions could be enhanced, especially as length of insect life cycles may be reduced [45]. In warmer parts of Europe termites, especially subterranean termites (of the *Rhinotermitidae* family) are endemic. These are spreading northwards and across the English Channel [46], so are likely to pose a special risk under a changing climate where temperatures are high and well drained soils persist. This hints at the complexity of the interactions between biological attack, soil and climate, so means that simple indices can only be indicators. It is likely that models of life cycles of heritage pests are important in predicting future threats to timber heritage, perhaps following the lines of those used in defining future risks for forests [47].

Modelling future risk

There is a loose correlation with the long-term changes in Scheffer indices across Europe as calculated from the observed data and the modelled values presented in [7], extracted into the European map shown as Fig. 7a. This map is derived from the differences between the Scheffer indices 1984/2013 and 1850/1879 as derived from HADGEM-GC31-MM CMIP6 under the Shared Socio-economic Pathways 585 [6]. It suggests decreases in the

Scheffer index in the Mediterranean and increases in North-western Europe. Vienna shows little change in both the values derived from models and observations. However, the Russian Arctic reveals a decrease in the modelled estimates, while the Scheffer indices derived from observations would suggest modest increases. Marseille shows little change on the modelled values, but those from observations suggest a slight increase.

Over the 21st century the Scheffer index is likely to change more dramatically than in the past (Fig. 7). Large changes are projected for the Atlantic coasts of the British Isles and Norway, where the changes might mean an increase of about 50 to the index. The British Isles are already at moderate risk, so this increase potentially poses a substantial threat to timber heritage. Much of Fennoscandia will see substantial increases that will also be found in the Alps. The boreal climates are now typically in the low-risk category, but at the end of the century risks are likely to be higher. In temperate Europe, a modest increase of about 10 Scheffer units is expected, but in some places this will cause these areas to go from medium to high risk by the end of the century. The Iberian Peninsula and Mediterranean Europe looks set to benefit from a reduced risk through the 21st century.

The modelling output presented here supports decisions in managing heritage, yet is not always accompanied by long observational record. Furthermore, data may not always be available close to heritage sites of interest or across the right time window to strengthen

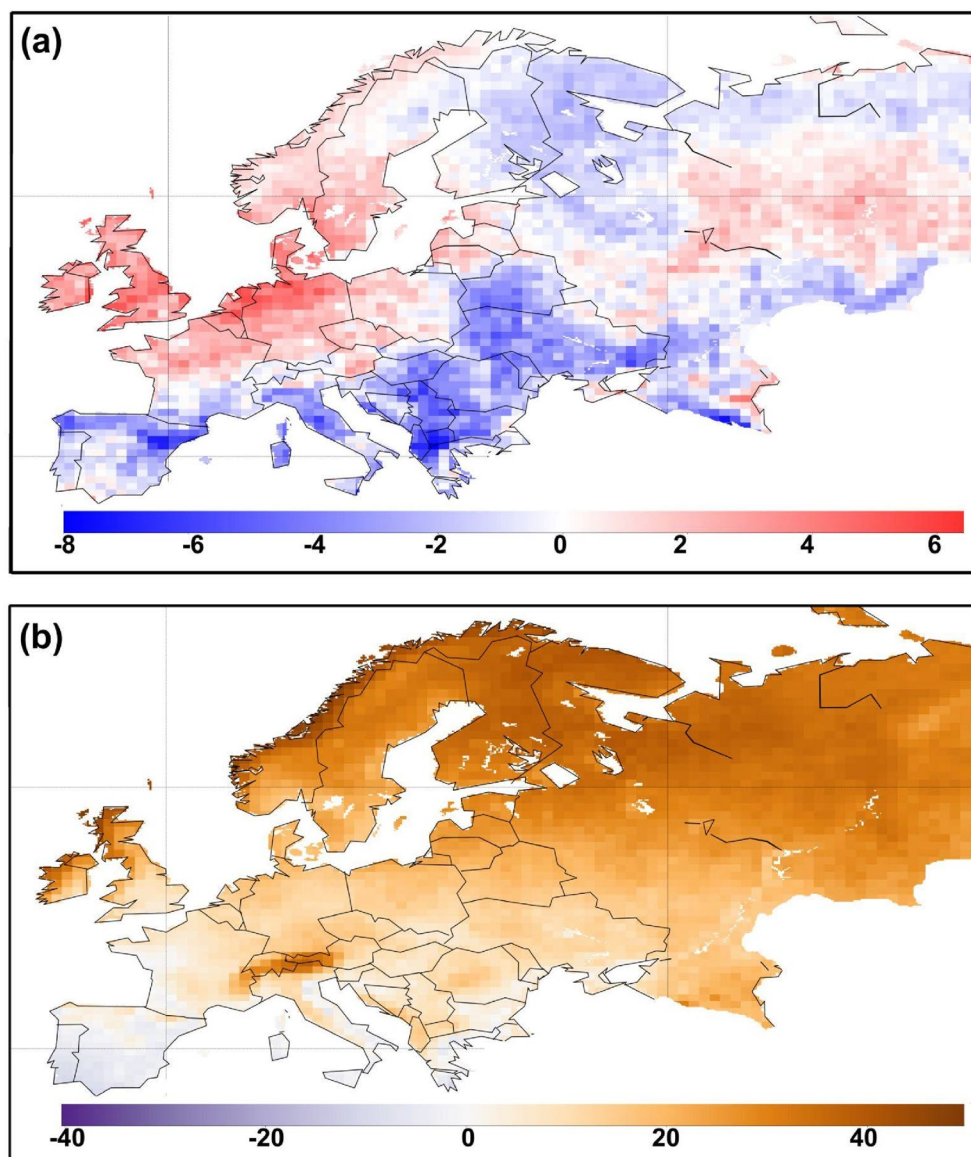


Fig. 7 Difference in the Scheffer index in the past between **a** 1984/2013 and 1850/1899 and **b** 2070/2099 and 1984/2013 extracted from data presented in Richards and Brimblecombe [7]. Scales are different to capture the greater range of change in the future

conviction about the accuracy of results. Often climate data has gaps or is only available as monthly averages in historical trends. It is not always possible to transform monthly data to the daily values inherent in the Scheffer index [28] and other heritage climate parameters such as freeze thaw events can be especially difficult to estimate from monthly data [28].

Predictions and model output of future climate or rates of damage are sensitive to input errors and model reliability. Such problems have implications for management decisions. Although they have rarely been the subject of research, recent Richards et al[27] demonstrate the use

of a multi-model ensemble approach in examining error propagation. Particularly important from a management perspective is that there is good agreement between models about the direction of change in locations where the Scheffer index was greatest. This suggests management decisions about future threat to timber assessed from the Scheffer index would be fairly robust as they would reliably determine areas where the risk to timber was likely to get worse. Therefore, extending such assessments of error to European timber heritage, could represent a useful analysis for managers.

Conclusions

The threat to timber heritage has increased in the temperate and continental regions of Europe, though it has decreased along the northern Mediterranean coast. The threat remains comparatively low in high latitude regions. The direction of change provides useful information for policy makers, and fortunately this is likely to be more robust than estimates of the magnitude of the threat. Although Köppen classes are a rough indicator of Scheffer indices (a heritage climate parameter similarly based on temperature and precipitation) the classes are not entirely satisfactory as a large range of Scheffer indices are found within a given class. Thus, properly tuned parameters and indices are needed by heritage science, which may also aid future exploration of risks from fire, landslides, insects etc. It would also be of use to develop a Scheffer-based index tuned to older drier timber, and to capture risk at a monthly or seasonal resolution as seasonality has implications for biological susceptibility and site management. Further research is needed to evaluate error in modelled output and the problems imposed by high risks in extreme years, and address the interactions between biological and climate-imposed risks to timber.

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PB Conceptualisation, methodology, data curation and analysis, visualisation, writing and editing. JR Data visualisation, writing and editing.

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Availability of data and materials

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

The authors declare that they have no conflicts of interest in this work. We declare that we do not have any commercial or associative interest that represents a competing interest in connection with the work submitted.

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