Heritage Science

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Assessing different measures of fire risk for Cultural World Heritage Sites

Martin Thomas Falk[1] and Eva Hagsten[1*]

Abstract

This study aims to assess whether two publicly available sources of fire threats to 346 Cultural World Heritage Sites across Europe substitute or complement each other. By doing so, a novel measure based on information from the UNESCO periodic report II is created and benchmarked against the European forest fire information system (EFFIS) index. The UNESCO periodic report shows that forest fires are perceived as an actual or foreseeable hazard by 40% of the management of Cultural World Heritage Sites in Europe. When the EFFIS index is linked to the UNESCO World Heritage database, it occurs that 48% of these sites are at high risk of fire, 31% at medium risk and 21% at low risk. Results based on Probit and Fractional Probit estimations reveal that the perceived fire risk relates to several site characteristics as well as location. The regressions using the EFFIS index as dependent variable show indifference to site characteristics even if location is of importance. Estimations give that the perceived fire risk is highest for sites in the East and the North of Europe, while the results for the EFFIS index lead to a dominant risk in the South. A 10° increase in latitude (corresponding to the distances between Vienna and Stockholm or Athens and Vienna) leads to a considerable decrease in the proportion of high fire risk by 28 percentage points (with a sample mean of 48%). Thus, the two measures of fire risks complement rather than substitute each other. Latitude is of no importance for the site managers, although the EFFIS gives this aspect a heavy weight, with low or zero risks in locations at higher latitudes (Iceland, Ireland, Latvia, and Norway) and larger risks in Southern Europe (Cyprus, Malta, Portugal, Albania, Spain, and Greece). In addition, the perception of (wild)-fire threat is significantly lower for cities.

Keywords Cultural World Heritage Sites, Fire risk, Wildfire, Heritage management, EFFIS, Latitude, Modelling

Introduction

Cultural World Heritage Sites are threatened not only by possible overuse or wear [1] but also by various climate and extreme weather factors including sea level rise and floods [2–4], air pollution and greenhouse gas emissions [5] as well as droughts, heatwaves and temperature increases [6–10]. Far less research is found on the harm that fires may pose to a site. Many cultural heritages are potentially threatened by fires, as wood is a common material in old buildings [11–14]. Bosher et al. [15] find that fires are among the most prevalent hazards to cultural heritage sites (including several listed by UNESCO) besides earthquakes and floods. There are also cultural sites that are embedded in forested landscapes and thus are equally at risk from fires [6, 12]. Oh et al. [16] show that the threat of decay in cultural heritage sites with wood components will increase with climate change. Globally, wildfire size, severity, and frequency are increasing over decades and climate change is considered one of the main factors behind this [17–20].

This study aims to assess whether two publicly available sources of fire threats to 346 Cultural World Heritage Sites across Europe substitute or complement each other. By doing so, a novel measure based on information from the UNESCO periodic report II [21, 22] is benchmarked

*Correspondence:
Eva Hagsten
Eva.m.hagsten@usn.no
[1] School of Business, University of South-Eastern Norway (USN), Campus Bø, Gullbringvegen 36, 3800 Bø, Norway

against the index of the European forest fire information system (EFFIS) [23]. Both these measures are linked to the World Heritage Database [24] allowing the inclusion of location as well as site characteristics as explanatory variables. Besides size of the site and year of inscription, dummy variables are employed for each of the following variables: country group or latitude, kind of site (city, religious site, cultural landscape), UNESCO inscription criteria, inclusion of wooden material, forests or other combustible material. Actual or potential wildfire threats in the UNESCO periodic report are identified on a binary scale by each single site management. This binary scale is transformed into an index where the proportion of sites with a high risk of fires is estimated using a Probit model. The determinants of the EFFIS high-fire risk index (based on historical fires, weather parameters and combustible materials) are estimated using a Fractional Probit model, since approximately one out of ten sites are located in areas with no risk.

There are several studies that model the relationship between climate change and cultural heritages. Leissner et al. [25] examine both the outdoor risks to cultural property resulting from climate change and the threats to indoor collections. Vulnerability of wooden cultural heritages in Korea to the impacts of climate change is investigated by Oh et al. [16] based on the decay risk and the climate change index developed by Scheffer [26]. Brimblecombe and Lefèvre [5] model long term effects of weather changes and air pollution on the stone façade, metals and stained glass of Notre-Dame in Paris. A literature review by Richards and Brimblecombe [27] finds that empirical modelling in the field of heritage sites is still scarce. In general, methods for modelling wildfires are increasingly advanced with machine learning and data mining techniques (see for instance [28, 29]). There are also quite a few studies that investigate the type of threats to Cultural World Heritage Sites, including those from wildfires based on the UNESCO periodic reports. For instance, Falk and Hagsten [30] model the degree of actual threats to Cultural World Heritage Sites, but do not consider potential threats. Birendra [31] examines the threats to a selection of World Heritage sites that are classified as being in danger. These sites face multiple challenges, although fire hazards are rarely mentioned [31].

Knowledge of the factors and characteristics that make a World Heritage Site threatened by fire is important for several reasons. During the last decades, climate and land use have exhibited an increased prevalence of mega-fires in the Mediterranean-type climate regions (MCRs) [32]. Approximately 90% of recent wildland fires appearing in the south of Europe are caused by human activities [33]. In a review, Ganteaume et al. [34] state that in Europe, humans cause almost all fires, and in the European Mediterranean region, most of them are caused intentionally. Considering comparable data reported for 19 European countries in the EFFIS Fire Database for 2016, only 4% of the fires are found to occur without human interference, most of these cases caused by lightning [35]. However, UNECE [36] points out that in many parts of the world, a large proportion of forest fires have unknown causes.

Both Salazar et al. [13] and Garcia-Castillo et al. [14] discuss the applicability of available fire risk assessment measures on different kinds of cultural heritage sites (buildings, towers, historic centres, archaeological sites, bridges, statues, et cetera.). These measures consider various aspects of the fire risk, including past fire events, building characteristics, utilities, fire protection measures and fire preparedness. The reviews by Both Salazar et al. [13] and Garcia-Castillo et al. [14] also make it clear that there are no internationally comparable measures available.

By linking data from three different sources (the UNESCO periodic report II [21, 22], the EFFIS database [23], and the World Heritage database [24]), this analysis contributes not only a novel generic measure of fire risks based on perceptions for the future to be benchmarked against an existing composite index with strong historical elements. It also uncovers the importance of site characteristics and location for the fire risk. This approach implies that an assessment can be made about whether the two sources of fire risks substitute or complement each other.

The study is structured as follows. "Methods and materials" section presents the methods and materials. Descriptive statistics and the empirical results are reported in "Descriptive statistics and empirical results" section. This then shifts into the discussion of the findings before finally turning to the conclusions, limitations and recommendations for future research "Conclusions" section.

Methods and materials

The methodological approach pursued in this study can be expressed as a flow chart (Fig. 1). Steps included are the statement of the purpose, through data collection and linking, to the model specifications, and the final phase of creating and comparing the fire threat probability measure with the EFFIS fire risk index.

Empirical approach

While cultural heritage buildings often hold significant aesthetic and, historical value, they are also frequently vulnerable to fire [11–14]. Two separate ways of measuring fire events are found in literature. One is the

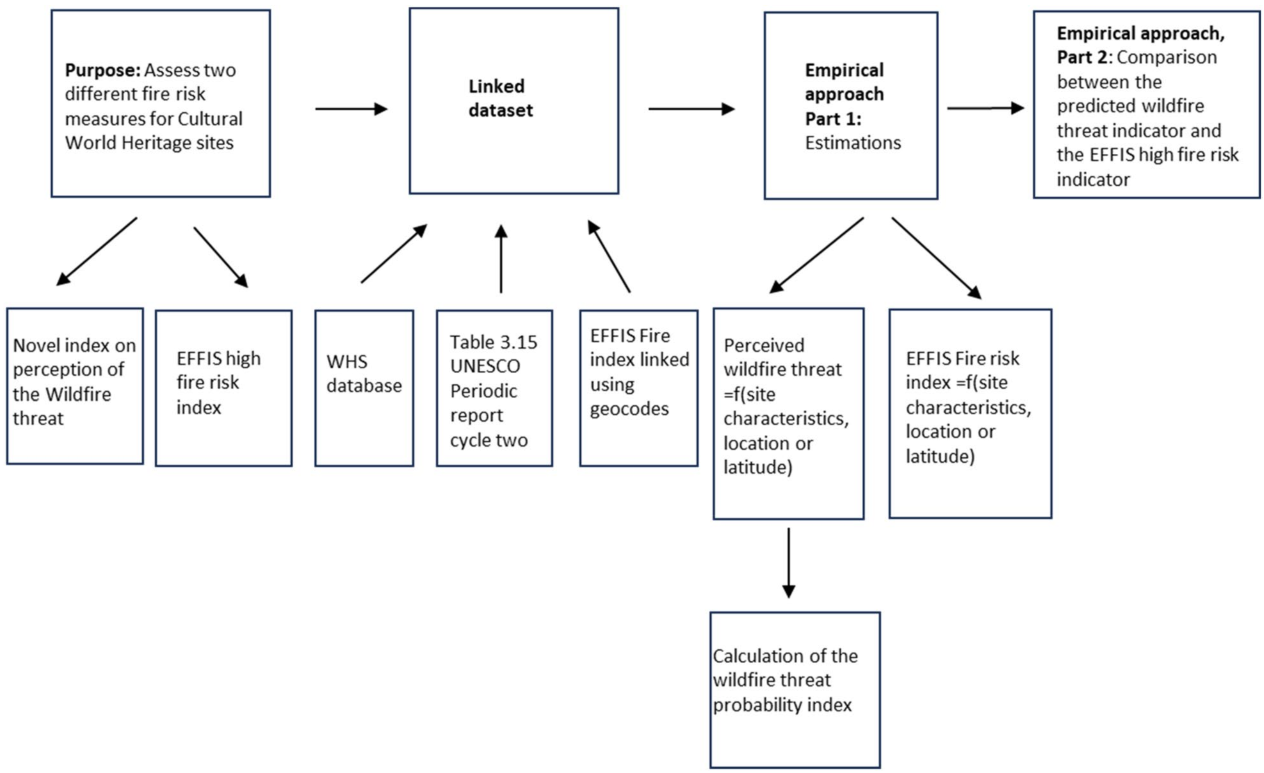

Fig. 1 Overview of the methodological steps (Source: Own illustration)

probability or fire susceptibility in a given area and time span and the other is the extent of the fire measured as the number of fires or surface burnt [33–35, 37]. Another is a composite measure of the fire risk as a function of both the probability of a fire and the amount of damage it could cause [34]. Salazar et al. [13] provide a comprehensive review of available fire risk indices that can be used for existing cultural properties. These indices take into account different aspects of fire risk, namely past fire events, building characteristics, utilities and fire protection measures. However, they are only available at the national level or for specific buildings. In this study, the EFFIS measure [23] represents a composite area specific index while the actual or potential threat of a wildfire as perceived by the heritage managers [21, 22] is site specific.

In literature, factors used to model wildfire susceptibility include topography (elevation, slope), anthropogenic or human activities (population density), vegetation (forest density, grassland, fuel type, soil moisture) as well as climatic and weather factors (temperatures, wind, precipitation) [38–41]. Weather conditions are particularly important for predicting short-term fire behavior on an hourly or daily basis. For instance, short-term changes in precipitation, humidity, temperature, and solar radiation can affect fuel moisture, or sudden changes in wind strength may have a large effect on how the fire spreads [42]. In the long run, the climate conditions become more important as they determine fire patterns over annual, decadal, or longer time periods [40]. Other long-term factors are population density and vegetation type [40].

Determinants of fire probability are usually modelled by Logit or Probit models, while the number of fires or fire density is a count data that can be estimated by Poisson or negative binomial regression models [40, 43–45] in combination with spatial econometric methods [46]. In this case, the binary information of the wildfire threat perception is specified as a Probit model. Based on these estimates, the predicted probabilities of perceived fire threats are calculated for different kinds of heritage sites and their locations. This constitutes the novel measure of fire threats. The explanatory variables are inspired by recent literature and represent human, vegetation, climate and topography aspects. In addition to this, the sites are characterised by kind: city, cultural landscape or religious. Inflammable material is approximated by the presence of wood or trees in the World Heritage description (World Heritage list, column "short_description_en"). Climate conditions are expected to be represented by the location of the site. Four country groups are used for the analysis:

Northern, Southern, Western and Eastern Europe, where South France is defined south of the 45° latitudes, approximately a line between Bordeaux and Valence [47]. Thus, based on the theoretical and conceptual considerations outlined above, the perceived threats of fire are transformed into probabilities, specified as a function of location and site characteristics X (Eq. 1):

$$FIRETHREAT_i^* = \alpha_0 + \beta_1 Size_i + \beta_2 Dateregistered_i + \beta_3 Dangerlist_i + \sum_{K=1}^{3} \beta_{4K} Kind\_site_{iK} + \sum_{S=1}^{6} \beta_{5S} Selection\_criteria_{Si} + \sum_{C=1}^{3} \beta_{6C} Countrygroup_{Ci} + \beta_7 Transboundary_i + \beta_8 Latitude_i + \beta_9 Wood_i + u_i. \quad (1)$$

The link between the underlying dummy variable and the probability of fire is defined as follows:

$$FIRETHREAT_i = \left\{ \begin{matrix} 1 & FIRETHREAT_i^* > 0 \\ 0 & otherwise \end{matrix} \right\}.$$

where i is the Cultural World Heritage Site. $FIRETHREAT_i^*$ is the latent response variable representing the individual fire threat perception (actual and/or potential) to a Cultural Heritage Site based on data from the second reporting cycle [21, 22], α_0 is the constant and u_i is the error term. *Size* is the surface of the terrain measured in hectares, *Dateregistered* is the year of inscription to the World Heritage list and *Dangerlist* is a dummy variable if the Cultural World Heritage Site has been on the danger list in the past. The dummy variable *Kind_site* measures the kind of site spanning from cultural landscape and city to religious site). *Selection_criteria* is a set of dummy variables reflecting selection criteria for Cultural World Heritage Sites (C1–C6) and *Country group* is a set of country group dummy variables based on the location of the site where South France is assigned to Southern Europe. When a site is *Transboundary*, it is illustrated by a dummy variable that indicates whether the site stretches over two or more countries. As an alternative to the *Countrygroup* dummy variables, the latitude of the sites is considered. The dummy variable *Wood* is equal to one if the Cultural World Heritage Site is located in a forested landscape or has a wooden building.

The binary Probit model is estimated by Maximum Likelihood for the total number of Cultural World Heritage Sites in Europe who participated in the second periodic report published in 2014. Standard errors are clustered by country to account for aspects in common for sites located there.

The second dependent variable tested is the proportion of an area characterised by a high or medium to high risk for fire according to the already existing EFFIS index [23]. Just like as with the specification including perceptions of fire threats as a dependent variable, the EFFIS index is also regressed on location and site characteristics as explanatory variables.

The EFFIS index is a proportion bounded between zero and one, implying that a standard ordinary least squares estimator is not suitable since it may produce fitted values that exceed the lower or upper boundaries [48]. A common method to circumvent this problem is to estimate the Fractional Logit (or Fractional Probit) model [48]. This estimation method specifies a functional form for the conditional mean of the dependent variable so that the predicted values appear within the correct interval. Thus, the model on the fire risk including the EFFIS index is estimated by Fractional Probit Maximum Likelihood [48]. About 10% of the 346 Cultural World Heritage Sites considered, have a high risk of fire equals to zero.

Data sources

Data for the analysis originate from three different sources: the UNESCO Periodic Report Second Cycle Section II [21, 22] as well as the EFFIS [23] and the World Heritage [24] databases. Since natural or mixed sites experience different presumptive threats than cultural sites, the analysis is limited to the latter sites participating in the second reporting round and for which information is available. This leaves 346 Cultural World Heritage Sites for the exploration.

The UNESCO Periodic Report Second Cycle Section II conducted in 2014 is the most recent data source on management perceptions of fire risks at the time of the analysis. Table 3.15, titled "Factors Summary", contains information on negative and positive factors relating to World Heritage Sites. This table includes judgements for up to 80 factors in 14 sub-categories. Present analysis focuses on the threats listed in this table under the section labelled 3.11.6: "Sudden ecological or geological events". This listing also includes information about whether a threat is actual or potential. Fire (wildfires) as defined by UNESCO includes (i) altered fire regimes, (ii) high impact fire suppression activities, (iii) lightning strikes and (iv) accidental fires (human induced) (Source: https://whc.unesco.org/en/factors/ and questionnaire for definitions [49]). As fires are rare [50] and mainly appear in the summer season, no distinction between actual or potential is drawn in this study.

The EFFIS fire risk index originates from the first prototype version of the risk classification in Europe undertaken by the EU Joint Research Centre [23, 51]. In this database, the fire risk is a composite index encompassing four factors: (i) historical fire data independent of cause, (ii) Dead Fuel Moisture Content (DFMC), (iii) fuel types, consisting of vegetation types (flammable wildland: forests, other woodlands, and non-artificial/agricultural land with flammable vegetation) and (iv) climate conditions (wind, moisture, precipitation, and temperature) [51]. Three fire risk classes can be distinguished: (i) high, (ii) intermediate and (iii) low (Table 5, Appendix, reports the median and high fire risk values) with a simple score ranging from 0 to 100%. A vast majority of forest fires in Europe are due to human causes; by intentions, accidents or neglect [35]. These aspects are only partly covered in the UNESCO periodic report. Besides that, the major difference between the dataset underlying the computation of a new fire threat measure and the EFFIS index is that the former is based on perceptions of the future and the latter relates to a set of neutral components, partly related to the past.

The fire threat perceptions are linked to the World Heritage database [24] using the id number of the Cultural World Heritage Sites and the linking to the EFFIS database employs information on latitude and longitude for the area within which the heritage site is located. The information about the fire risk is shown for individual areas of 12.5 km multiplied by 12.5 km [23].

All explanatory variables relating to site specific characteristics (size of site, year of inscription, location, inclusion on the danger list and selection criteria) are found in the World Heritage database [24]. Listed as in danger are the Historic Centre of Vienna, the Liverpool—Maritime

Table 1 Descriptive statistics. Source: World heritage database [24], UNESCO periodic report II [21, 22], EFFIS database [23] and own calculations

	Unit	Obs	Mean	Std. dev	Min	Max
Dependent variables						
UNESCO negative factor	0/1 variable	346	0.40		0	1
EFFIS: high fire risk category	Proportion	346	0.48	0.40	0	1
EFFIS: high/ medium fire risk category	Percentage Proportion	346	0.79	0.32	0	1
Explanatory variables						
Area, hectares	Hectares	346	4374	21,771	0	302,319
Year inscribed	Year	346	1995	9	1978	2014
Wood in buildings or on the site	0/1 variable	346	0.09		0	1
Danger list	0/1 variable	346	0.02		0	1
Inscription criteria						
C1 masterpiece of human creative genius	0/1 variable	346	0.35		0	1
C2 architecture or technology, monumental arts, town-planning or landscape design	0/1 variable	346	0.58		0	1
C3 cultural tradition or to a civilization	0/1 variable	346	0.42		0	1
C4 building, architectural or technological ensemble or landscape	0/1 variable	346	0.75		0	1
C5 traditional human settlement, land-use, or sea-use	0/1 variable	346	0.13		0	1
C6 events or living traditions, ideas, artistic etc	0/1 variable	346	0.21		0	1
Kind of site						
Cultural landscape (reference category: other)	0/1 variable	346	0.20		0	1
City	0/1 variable	346	0.21		0	1
Religious site	0/1 variable	346	0.31		0	1
Other	0/1 variable	346	0.28		0	1
Transboundary	0/1 variable	346	0.03		0	1
Country group						
North Europe	0/1 variable	346	0.16		0	1
South Europe (incl. South France)	0/1 variable	346	0.46		0	1
Eastern Europe	0/1 variable	346	0.13		0	1
Western Europe (excl. South France)	0/1 variable	346	0.26		0	1

Mercantile City, the Medieval Monuments in Kosovo, the Natural and Cultural-Historical Region of Kotor, the Old City of Dubrovnik as well as the Wieliczka and Bochnia Royal Salt Mines. Cultural landscapes are defined in line with Rössler [52], and cultural cities are defined as having at least 5000 inhabitants. The identification of wooden material is based on the description of the World Heritage Site and a text mining exercise where the following keywords indicating inflammable material are used: *forest, tree, trees, timber, grass, bush, grassland, bushland*. Religious sites are identified with a similar approach with the keywords: *monastery, mosque, monastic, church, cathedral, basilica, abbey, temple, shrine, synagogue, chapel, holy place and churches*.

Descriptive statistics and empirical results

Descriptive statistics

Descriptive statistics show that two out of five site managers perceive wild forest fires as an actual or prospective hazard (Table 1). The proportion of cultural heritage sites with high fire risk is slightly higher (48%) and in the medium—high risk category 79%. Thus, one out of five sites falls into the low fire risk category. The proportion of sites with wood in buildings or on the site is 9%. With respect to kind of cultural site, 20% are landscapes, 21% are cities and 31% are spiritual. The size, measured in hectares, is 4374 on average, while the year of inscription is 1995. Two per cent of the sites appear on the list in danger of losing their inscription.

When the EFFIS fire risk index is linked to the Cultural World Heritage Sites, it appears that the category high fire risk is more dominant in the south than in the north of Europe (Fig. 2 and Table 5, Appendix, second column). This indicates that the fire risk measure is related to the latitude.

Estimation results

Estimations results reveal that the fire risk based on Cultural World Heritage Site management perceptions relate to several site characteristics as well as to location (Tables 2 and 3 as well as Figs. 3 and 4). The regressions using the EFFIS index as the dependent variable, on the other hand, show indifference to site characteristics (Table 3).

However, the assessment of the existing and newly computed measure also demonstrate that the deviation does not end there. While the perceived risk is highest for sites in the East and the North of Europe, the estimations including the EFFIS index lead to the opposite results, with the highest risks in the South. These results indicate that the two measures of fire risks complement rather than substitute each other.

The probability of actual or potential fire is 48 percentage points higher for Cultural World Heritage

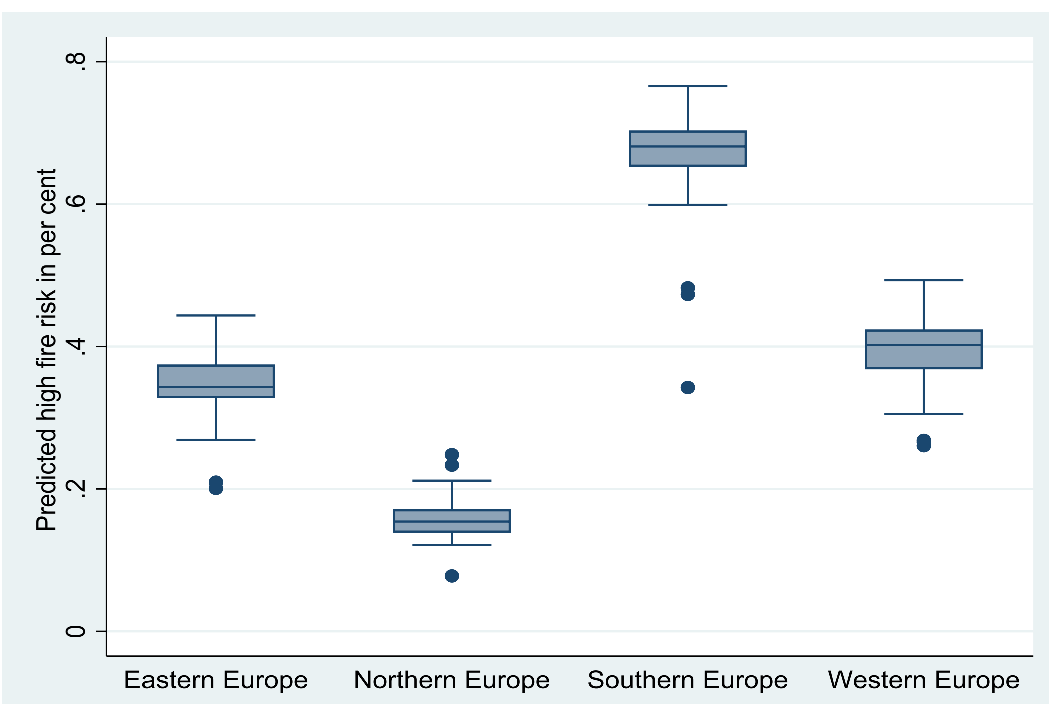

Fig. 2 High risk of fire in areas with Cultural World Heritage Sites, by country group (Source: EFFIS [23] linked to the World Heritage database (excluding mixed and natural sites) [24])

Sites in Eastern Europe than in the West (excluding South France) (p-value < 0.01). Sites in Northern Europe are those with the second highest perceived risk, 33 percentage points more than the reference category Western Europe (excluding South France) (p-value < 0.01). Cultural sites in the South of Europe (including South France) have a 30 percentage points higher fire risk than those in the reference category (p-value < 0.01).

Among the control variables, cultural landscapes with wood mentioned in the UNESCO description of the site (indoor or outdoor), trees or forests are found to have a higher fire risk, although the marginal effect is only weakly significant at the 10% level in the baseline regression. Cultural cities have a significantly lower risk for fires (p-value < 0.01) with a marginal effect of −0.23 (Table 2, Fig. 5). This means that the perception of fire risk is 23 percentage points lower than for the reference group of other sites (no religious sites or cultural landscapes). Size of the cultural site and year inscribed do not play a role in these threats, although those sites that are in danger of losing their inscription are facing a higher fire threat probability (p-value < 0.01).

When the country group dummy variables are replaced by latitude, the Probit estimates show that the probability of a fire threat is independent of latitude (p-value: 0.42) (Table 3). This means that the perceived fire threat is not declining with higher latitudes. The control variables cultural city and inclusions on the danger list are again significant at the 1% level while the variable "Wood in buildings or on the site" is significant at the 5% level (Table 3).

Contrary to the results based on the perceived fire risk, the Fractional Probit model estimations of the high fire risk index point to a clear importance of latitude. The proportion of high fire risk appears to be dominant in the South of Europe and weakest in the North (with p-values < 0.01) (Table 4). Calculated marginal effects show that the fire risk for sites in Southern Europe is 24 percentage points higher than in the reference category Western, while in the North, the risk is 27 percentage points smaller than the reference category. The country

Table 2 Probit estimations of perceptions of wildfire risks to Cultural World Heritage Sites. Source: UNESCO periodic report II for Europe, 2014 [21, 22], World Heritage database [23], own calculations

Explanatory variables	Coeff	z-stat	dy/dx	z-stat
Area in hectares	0.000	1.49	0.000	1.50
Year inscribed	−0.010	−1.16	−0.003	−1.19
Danger list	1.898***	3.34	0.588***	3.55
Wood in buildings or on the site	0.486*	1.80	0.151*	1.79
Inscription criteria				
C1 masterpiece of human creative genius	−0.574**	−2.38	−0.178**	−2.54
C2 architecture or technology, monumental arts, town-planning or landscape design	−0.121	−0.79	−0.038	−0.80
C3 cultural tradition or to a civilization	−0.297**	−2.21	−0.092**	−2.25
C4 building, architectural or technological ensemble or landscape	−0.221	−1.50	−0.068	−1.48
C5 traditional human settlement, land-use, or sea-use	−0.234	−0.96	−0.072	−0.94
C6 events or living traditions, ideas, beliefs, artistic and literary works	−0.451***	−3.41	−0.140***	−3.28
Kind of site				
Cultural landscape (reference category: other)	−0.121	−0.86	−0.037	−0.85
City	−0.745***	−4.15	−0.231***	−4.40
Religious site	0.231	1.57	0.072	1.63
Transboundary	0.004	0.01	0.001	0.01
Country group				
North Europe (reference category Western Europe)	1.093***	3.01	0.339***	3.26
South Europe (incl. South France)	0.964***	3.19	0.298***	3.48
Eastern Europe	1.536***	4.26	0.476***	5.02
Constant	19.869	1.14		
Number of observations	346			
McFadden's Pseudo R^2	0.189			

***, ** and * denote significance at the 1, 5, and 10% levels. The underlying dependent variable is the perception of negative factors (actual/or potential) due to wildfires to the (Cultural) World Heritage Sites. Non-European sites are not included. Standard errors are adjusted for 50 country clusters. dy/dx denotes the marginal effects.

Table 3 Probit estimations of perceptions of wildfire risks to Cultural World Heritage Sites (with latitude). Source: UNESCO periodic report II for Europe, 2014 [21, 22], World Heritage database [24], own calculations

Explanatory variables	Coeff	z-stat	dy/dx	z-stat
Area in hectares	0.000	1.26	0.000	1.27
Year inscribed	−0.011	−1.23	−0.004	−1.24
Danger list	1.646***	2.62	0.570***	2.74
Wood in buildings or on the site	0.537**	2.20	0.186**	2.17
Inscription criteria				
C1 masterpiece of human creative genius	−0.617***	−2.89	−0.214***	−3.18
C2 architecture or technology, monumental arts, town-planning or landscape design	−0.194	−1.35	−0.067	−1.35
C3 cultural tradition or to a civilization	−0.198	−1.23	−0.068	−1.23
C4 building, architectural or technological ensemble or landscape	−0.168	−1.07	−0.058	−1.07
C5 traditional human settlement, land-use, or sea-use	−0.083	−0.32	−0.029	−0.32
C6 events or living traditions, ideas, beliefs, artistic and literary works	−0.446***	−3.90	−0.154***	−3.93
Kind of site				
Cultural landscape (reference category: other)	−0.123	−0.88	−0.042	−0.87
City	−0.618***	−3.60	−0.214***	−3.76
Religious site	0.234*	1.82	0.081*	1.88
Transboundary	0.064	0.14	0.022	0.14
Location				
Latitude	−0.007	−0.42	−0.003	−0.42
Constant	22.031	1.26		
Number of observations	346			
McFadden's Pseudo R^2	0.098			

***, ** and * denote significance at the 1, 5, and 10% level. The underlying dependent variable is the perception of negative factor (actual/or potential) due to wildfires to the (Cultural) World heritage sites. Non-European sites are not included. Standard errors are adjusted for 50 country clusters. dy/dx denotes the marginal effects.

group dummy variable Eastern Europe is not significantly different from Western Europe. Just like with the estimation of the perceptions, this approach also tests whether latitude is of higher importance than the set of country group dummy variables. With this change to the specification, the estimations reveal that a high fire risk depends significantly negatively on latitude (p-value < 0.01). The coefficient of −0.031 indicates that a 10° increase in latitude (corresponding to the distances between Vienna and Stockholm or between Athens and Vienna) leads to a decrease in the proportion of high fire risk by 28 percentage points. This is a large magnitude given the sample mean of the proportion of high fire risk of 48%. As expected, the control variables measuring site characteristics are not significant at conventional significance levels.

As a robustness check, the dependent variable high risk category from the EFFIS dataset is replaced by the category medium high risk. This leads to similar results but with somewhat smaller marginal effects for latitude and the country group dummy variables. For instance, the coefficient for latitude is in absolute terms −0.026 instead of −0.031 in the baseline estimation (Table 4 and Table 6, Appendix). Another robustness check is the use of the Fractional Logit model instead of the Fractional Probit model. This renders similar results and thus is not reported here.

The predicted probabilities of the perceived fire threat obtained from the Probit estimates are calculated by country and compared with the EFFIS high fire risk index (Table 5, Appendix). The two measures are weakly significantly negatively correlated (r = −0.10 and the p-value < 0.10 based on the Pearson correlation coefficient and 346 Cultural World Heritage Sites) indicating that they rather complement than substitute each other. The predicted probability of fire threat is highest for Cultural World Sites in Montenegro, Romania, Hungary, Slovakia and Czechia ranging between 75 and 94% measured as the median (Table 5, column i, Appendix). In contrast, the EFFIS measure of the proportion of high fire risk is dominant in the Southern European countries (Malta, Cyprus, Portugal, Albania, Holy See, Croatia and Spain) ranging between 98 and 100% and the lowest threat is found in Northern Europe (Iceland, Ireland, Latvia, and Norway) (Table 5, column ii, Appendix). This clearly shows the composite EFFIS risk index has a strong spatial element. Thus, the judgments of heritage managers and the fire danger estimates using data from past events,

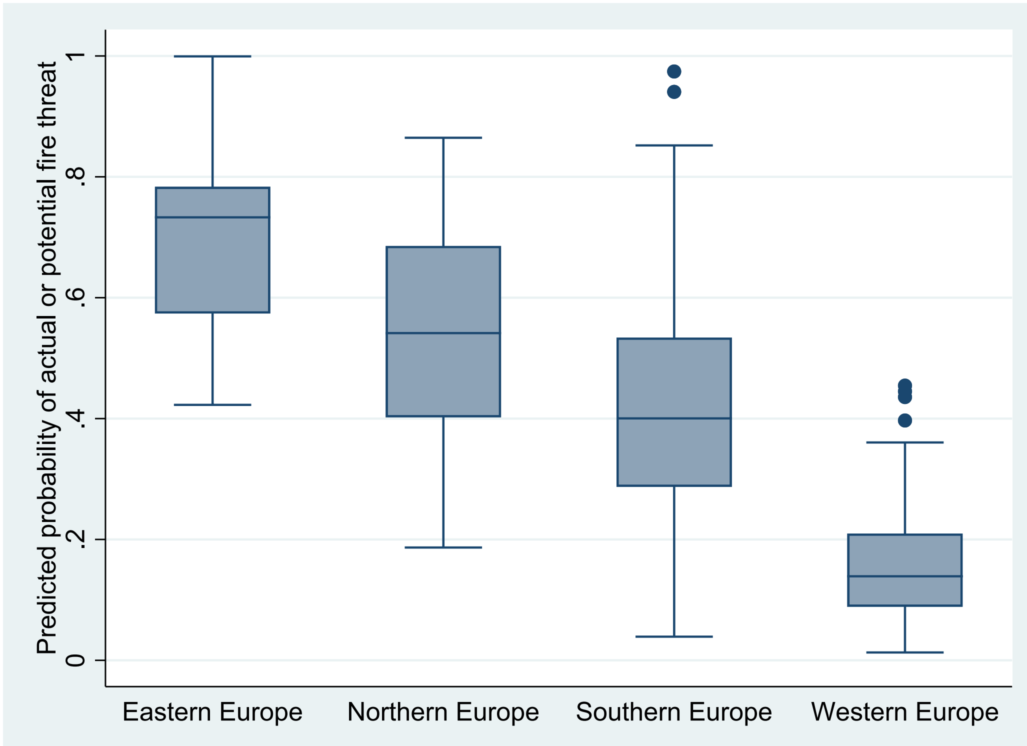

Fig. 3 Predicted probabilities of combined actual and potential fire threat by country group. Predicted probabilities are calculated using the Probit estimates reported in Table 2. The number of observations (Cultural World Heritage Sites) is 346 (Source: UNESCO periodic report II for Europe, 2014 [21, 22], World Heritage database [24], own calculations)

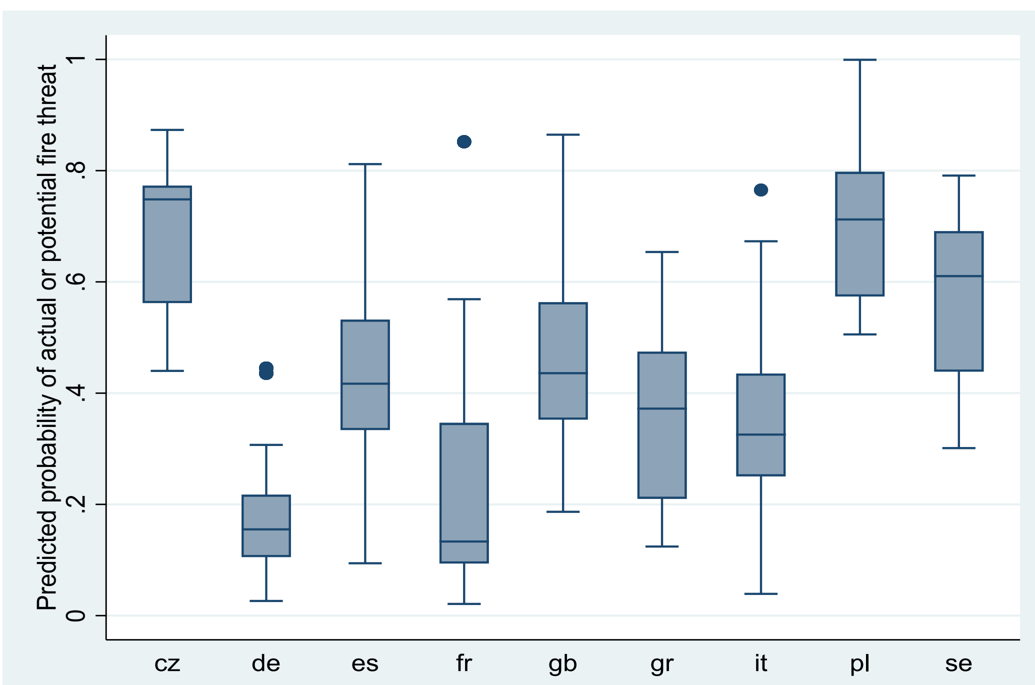

Fig. 4 Predicted probabilities of combined actual and potential fire threat by selected countries. Predicted probabilities are calculated using the Probit estimates reported in Table 2. cz, ...,se are the two-digit country codes (in lower case). The number of observations (Cultural World Heritage Sites) is 346 (Source: see Fig. 3)

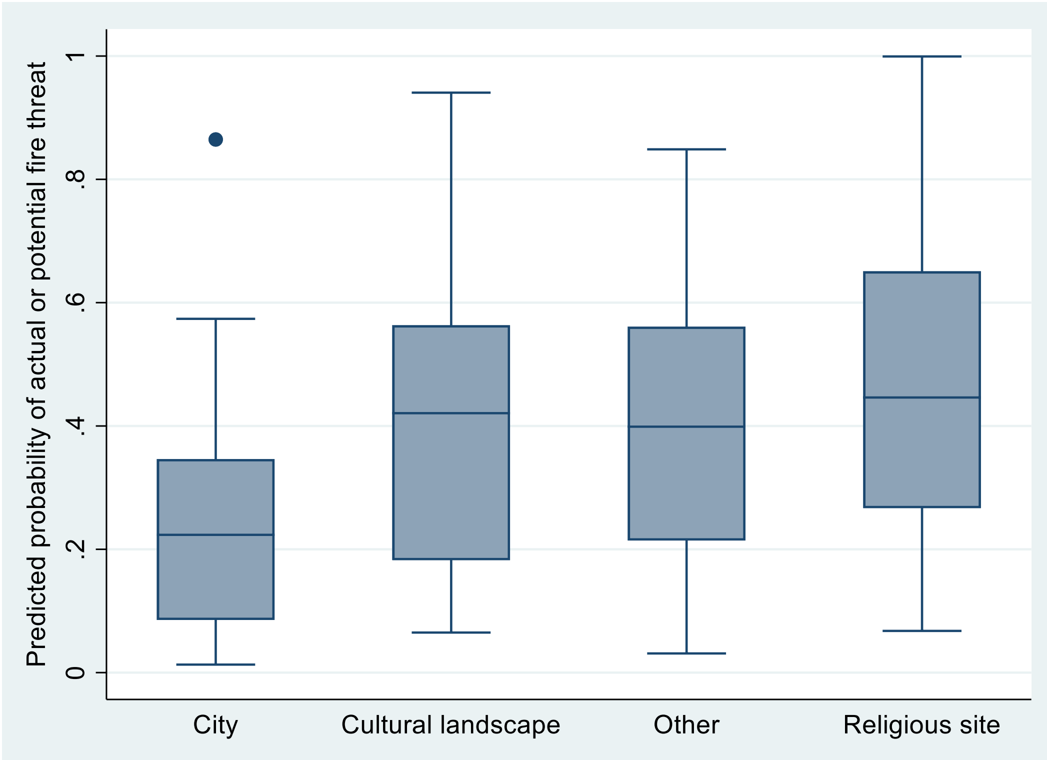

Fig. 5 Predicted probabilities of combined actual and potential fire threat by type of site. Predicted probabilities are calculated using the probit estimates reported in Table 2. The number of observations (Cultural World Heritage Sites) is 346 (Source: See Fig. 3)

weather patterns, and flammable material diverge substantially.

Discussion

An important finding of this study is that the two measures assessed indeed give different results. Cultural heritage managers in the south may underestimate the risk of fire while the EFFIS index dismisses that Cultural World Heritage Sites in the north and east of Europe may also be at risk. The EFFIS risk indicator is monotonously positively related to latitude and thus showing that the high fire risk category is predominant in the south of Europe. Certainly, the composition of and basis for the two different measures may explain why they do not fully overlap, that is, why they are not substitutes for each other. Thus, the assessment highlights that the measures complement each other and that they both would benefit from further development, including, for instance, local specifics.

According to the baseline model, World Cultural Heritage Sites with wooden elements do not appear to have a significantly higher perceived fire threat. This is surprising as sites with or made of wood generally have a high fire risk [13, 14] and many historic wooden buildings have been destroyed by fire disasters [13, 14, 53]. A possible explanation is that fire prevention measures are improving over time, especially in developed regions like Europe. Alternatively, the variable used lacks precision.

An absence of higher fire risk for cultural landscapes is also somewhat surprising, as such risks are known to be high in cultural landscapes within or surrounded by forests [12]. Possibly, the argument of developed regions and good fire protection equipment may play a role in the relationship.

Several implications can be drawn from the results. First, perceptions of wildfire risk for Cultural World Heritage Sites provide a realistic picture of the importance of local and site knowledge associated with external threats such as wildfires. Local knowledge of wooden elements of the site or whether it is surrounded by trees, or a forest might also be crucial. Population density also appears to be important, as indicated by the significance of the city dummy variables. Cultural cities have a lower fire risk,

Table 4 Fractional Probit estimations of perceptions of wildfire risks to Cultural World Heritage Site. Source: World Heritage database [24] linked to EFFIS fire risk data [23], own calculations

Explanatory variables	Specification (i)		Specification (ii)	
	dy/dx	z-stat	dy/dx	z-stat
Area in hectares	0.000**	−2.04	0.000	−1.25
Year inscribed	−0.001	−0.25	0.001	0.36
Wood in buildings or on the site	0.023	0.37	0.067	1.03
Danger list	0.016	0.09	0.028	0.17
Inscription criteria				
C1 masterpiece of human creative genius	0.039	0.63	0.040	0.66
C2 architecture or technology, monumental arts, town-planning, or landscape design	−0.005	−0.10	0.004	0.10
C3 cultural tradition or to a civilization	−0.002	−0.05	−0.010	−0.35
C4 building, architectural or technological ensemble or landscape	−0.003	−0.07	−0.021	−0.43
C5 traditional human settlement, land-use, or sea-use	0.073	1.03	0.092	1.29
C6 events or living traditions, ideas, beliefs, artistic and literary works	0.025	0.58	0.024	0.63
Kind of site				
Cultural landscape (reference category: Other)	0.031	0.73	0.013	0.30
City	0.025	0.60	0.042	1.07
Religious site	−0.024	−0.65	−0.020	−0.55
Transboundary	−0.131	−1.16	−0.133	−1.27
Country group/location				
North Europe (reference category Western Europe)	−0.266***	−3.09		
South Europe (incl. South France)	0.240***	3.65		
Eastern Europe	−0.037	−0.39		
Latitude			−0.031***	−9.61
Number of observations	346		346	
McFadden's Pseudo R^2	0.126		0.135	

Asterisks ***, ** and * denote significance at the 1, 5, and 10% levels. dy/dx denotes the marginal effects. The underlying dependent variable is the proportion of high fire risk category. Non-European sites are not included. Estimated with STATA using the fracreg probit estimation command

possibly because there is either less combustible material or because the level of prevention measures is higher. The geographical pattern with the highest perception of fire risk in Eastern and then Northern European locations is stable when location characteristics are taken into account.

Another important finding is that the threat of forest fires is also present in higher latitudes and colder climates where the Cultural World Heritage Sites are located. There are several reasons supporting the perception that areas at high latitudes are at risk of fires, such as long daylight in the summer, large forest areas and year-round forestry activities. Sjöström et al. [54], for instance, state that machine-caused forest fires are a major hazard in high-altitude areas such as Sweden. These fires can be largely avoided by cancelling operations in stony terrain during high-risk seasons. Managers could, for instance, monitor the threats and occurrence of fires using ICT solutions and web-based GIS platforms, as well as decision support tools such as manuals or emergency plans, to protect cultural heritage from fires and related hazards [55].

Conclusions

Cultural World Heritage Sites are threatened by many factors such as natural hazards and climate change. One of the largest threats is fires. Evidence based on the UNESCO second period report for Europe shows that 40% of cultural heritage managers believe that wildfires are an actual or potential threat to their site. The EFFIS fire risk database linked to the Cultural World Heritage Sites in Europe, on the other hand, shows that 48% of sites in Europe fall into the "high fire risk" category.

This study assesses the fire threat to Cultural World Heritage Sites as well as their determinants based on two different measures. A novel measure is created based on the binary information on perceptions from the UNESCO periodic report. This measure is benchmarked against the EFFIS wildfire index which is a scientifically computed composite indicator. Both the fire threat probability and the fire risk indicator are related to a number of site characteristics from the UNESCO World Heritage database as well as location and latitude using Probit and Fractional Probit models to account for the nature of the dependent variables.

Results of the study demonstrate that the two measures assessed give different results. Cultural heritage managers may underestimate the fire risk for sites in the South of Europe while the EFFIS index dismisses that Cultural World Heritage Sites in the north and east of Europe may also be at risk for fire. Cultural heritage sites with wood (indoor or outdoor) or trees and forests (such as cultural landscapes) are not considered to be at higher fire risk. One explanation is that the site description-based text mining analysis is not fine-tuned enough to provide a reasonably useful indicator of the use of wood in the structures and surrounding forest. Another explanation is the prevention measures at European sites. The perception of (wild)-fire risk is also significantly lower for cities. An implication of the study is that both measures, although generic, cannot be used as substitutes. Instead, they are both in need of further development.

This analysis has several limitations. First, the study is limited to Cultural World Heritage Sites in Europe, and second, it is a cross-sectional dataset. The UNESCO reports are regular but appear with long time intervals, implying that this dataset is not particularly well suitable for dynamic analyses. There are several ideas for future work. One idea is to develop specific fire risk indicators for different seasons. In the Northern latitudes, there is long daylight during the summer seasons, which might increase the fire risk even without particularly high temperatures. Future work could also extend the analysis to other continents.

Appendix

See Tables 5, 6.

Acknowledgements

Not applicable.

Table 5 Fire risk and fire threats by country (median). Source: EFFIS [23], UNESCO periodic report II [21, 22], the World Heritage Database [24]

Country	Predicted probability of fire threat	Proportion of high fire risk
Albania	0.56	0.99
Andorra	0.73	0.54
Austria	0.17	0.04
Belgium	0.12	0.01
Bosnia and Herzegovina	0.52	0.50
Bulgaria	0.65	0.16
Croatia	0.46	0.98
Cyprus	0.57	1.00
Czechia	0.75	0.33
Denmark	0.71	0.01
Estonia	0.42	0.00
Finland	0.69	0.05
France	0.13	0.37
Germany	0.17	0.50
Greece	0.37	0.86
Holy See	0.11	0.99
Hungary	0.76	0.85
Iceland	0.40	0.00
Ireland	0.50	0.00
Italy	0.33	0.79
Latvia	0.38	0.00
Lithuania	0.41	0.00
Luxembourg	0.09	0.32
Malta	0.66	1.00
Montenegro	0.94	0.03
Netherlands	0.11	0.41
Norway	0.71	0.00
Poland	0.71	0.02
Portugal	0.38	1.00
Romania	0.85	0.44
San Marino	0.35	0.81
Serbia	0.54	0.52
Slovakia	0.76	0.02
Spain	0.41	0.98
Sweden	0.61	0.06
Switzerland	0.23	0.05
Turkey	0.34	0.35
Ukraine	0.56	0.07
United Kingdom	0.44	0.22
Transboundary	0.42	
Total	0.39	0.43

Predicted probabilities are calculated using the Probit estimates reported in Table 2. The number of observations (Cultural World Heritage Sites) is 346. The EFFIS high fire risk index is linked to the Cultural World Heritage Sites using information on latitude and longitude

Table 6 Fractional probit estimates of the medium high fire risk to Cultural World Heritage Sites. Source: World heritage database [24] linked to EFFIS fire risk data [23], own calculations

Explanatory variables	Specification (i)		Specification (ii)	
	dy/dx	z-stat	dy/dx	z-stat
Area in hectares	0.000	0.02	0.000	0.41
Year inscribed	0.000	−0.28	0.000	0.26
Danger list	0.057	0.50	0.036	0.32
Wood in buildings or on the site	−0.036	−1.05	0.016	0.42
Inscription criteria				
C1 masterpiece of human creative genius	0.018	0.42	0.021	0.44
C2 architecture or technology, monumental arts, town-planning or landscape design	−0.017	−0.54	0.000	0.00
C3 cultural tradition or to a civilization	−0.064**	−2.58	−0.040*	−1.75
C4 building, architectural or technological ensemble or landscape	0.005	0.17	−0.007	−0.24
C5 traditional human settlement, land-use, or sea-use	−0.013	−0.24	0.027	0.43
C6 events or living traditions, ideas, beliefs, artistic and literary works	0.026	0.71	0.041	1.16
Kind of site				
Cultural landscape (reference category: other)	0.000	−0.01	−0.024	−0.63
City	−0.016	−0.57	−0.007	−0.25
Religious site	−0.020	−0.72	−0.016	−0.57
Transboundary	−0.120	−1.65	−0.133*	−1.76
Country group/location				
North Europe (reference category: Western Europe)	−0.153***	−2.98		
South Europe (incl. South France)	0.301***	4.14		
Eastern Europe	−0.037	−0.56		
Latitude			−0.026***	−8.85
Number of observations	346		346	
McFadden's Pseudo R^2	0.23		0.21	

Asterisks ***, ** and * denote significance at the 1, 5, and 10% levels. dy/dx denotes the marginal effects. The underlying dependent variable is the proportion of the medium–high fire risk category. Non-European Cultural World Heritage Sites are not included. Estimated with STATA using the *fracreg* probit estimation command

Author contributions

MTF Conceptualisation, methodology, data curation and analysis, visualisation, writing and editing. EH Conceptualisation, methodology, data curation and analysis, visualisation, writing and editing. Both authors equally contributed to each single part of the study.

Funding

Not applicable.

Availability of data and materials

All material employed in this study originates from official open access databases, which are referenced in the text, and processed by the authors. Data and STATA code are available from the authors on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Geolocation information

Europe.

Competing interests

The authors declare no competing interests relating to this study. There is no commercial or associative interest that represents a competing interest in connection with the research submitted.

Received: 19 June 2023 Accepted: 14 August 2023
Published online: 07 September 2023

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Martin Thomas Falk Professor, University of South-Eastern Norway (USN), School of Business, Campus Bø, Gullbringvegen 36, 3800 Bø, Norway

Eva Hagsten Associate Professor, University of South-Eastern Norway (USN), School of Business, Campus Bø, Gullbringvegen 36, 3800 Bø, Norway.