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Review

Environmental Forest Fire Danger Rating Systems and Indices around the Globe: A Review

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Abstract: The objective of the present review is to analyze and evaluate the most used and well-performing environmental forest fire danger rating systems and indices globally, aiming to the creation of an integrated forest fire danger system for Greece. The analysis emphasizes the core input parameters that have been associated with forest fire danger (i.e., weather, vegetation, topography, and hydrology) and the computational procedure of each system index as well as the categorization of the output values. Online search engines such as Scopus, Google Scholar, WorldWideScience, ScienceDirect, and ResearchGate were used in the search for relevant literature published in scientific journals, manuals, and reports. The retrieved studies were classified and reviewed. Studies were selected for analytically describing the calculation process related to forest fire danger ignition and not being strictly geographically bound. A total of 210 studies were included in the current review, describing 63 forest fire danger systems and indices. These were analyzed and evaluated based on a scoring system. Overall, the top-rated indices were the: Nesterov's index, Sharples' index, Keetch and Byram's drought index, Telicyn logarithmic, and vapor pressure deficit, and the 3rd and the 4th also proved to be the most accurate for fire-prone regions. Remote sensing indices also proved to be promising in forest fire danger estimation.

Keywords: forest fire; fire danger rating systems; environmental fire danger; fire indices; drought indices; remote sensing fire indices; fire ignition probability; climate change extremes

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1. Introduction

The role of forests—which cover approximately 31% of the global land [1]—is of great importance in ecological-environmental and socio-economic terms [2]. However, internationally, there has been a radical increase in the annual number of forest fire danger days and forest fire incidents, with climate change being one of the major contributors [3–10]. During the past two years, more than 45 million hectares have been burned across regions in Russia, Brazil, Canada, the United States of America, the European Union, and Australia [11–16], where forested areas cover 56% of the global forest land [1,17,18].

Several studies and reports indicate that most of the forest fire incidents are man-driven, in the form of either arson or negligence [19–24]. Nevertheless, wildfires occur mostly during periods of high temperature, intense drought, strong winds, low relative humidity, and inadequate precipitation [25–27].

Fire danger rating systems and indices are the products of systematic research both in theoretical and in empirical terms. Hence, many environmental fire danger rating systems throughout the world focus on the calculation of the condition of dead or alive fuels, such as fuel moisture codes, alongside meteorological parameters that have an impact on the source of heat as well as the ambient oxygen supply [28–31]. However, these systems ignore the human-driven ignition causes, with the latter being covered to a certain extent in the related literature [19–21,32–38]. Furthermore, only a limited number of studies adopts an integrated and/or holistic approach combining natural and human-driven causing factors as well as weather indices and conditions [39–41].

The objective of this review article is to report, analyze, compare, and evaluate the most applied and well-established environmental fire danger rating systems and indices around the world, aiming at the development of an integrated fire danger rating system for Greece.

2. Materials and Methods

Adopting the approach by Chuvieco et al. [34], fire risk assessment consists of two pillars: danger and vulnerability. Fire danger—also reported as fire hazard—is related to the conditions that favor the fire outbreak and its spread, while vulnerability is related to the possible outcome of a fire event as far as effects and value loss are concerned [34,42,43].

The present article focuses mainly on systems and indices that estimate fire danger ignition probability related to environmental factors as proposed by Cardille et al. [33]. The present review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guides for systematic reviewing; thus, the following selection criteria for the considered references were set [44]: (1) studies must be papers published in scientific journals, manuals that are operationally in use, or technical documents supporting fire agency policies; (2) studies must contain systems or indices that focus on fire ignition probability; (3) studies must include systems indices that are not strictly geographically bound; and (4) the indices and systems must include environmental input parameters (such as weather, vegetation, hydrology, and others). Although there are already several research and review articles related to fire danger rating systems [45–50], to the best of our knowledge, the present study is the most complete as far as the number, the geographical scale, and the analysis of the computational procedure of systems and indices are concerned.

The research commenced with the examination of fire danger rating systems currently in use in countries with significant fire history and forest land, such as the USA, Canada, Russia, and Brazil, in the official websites of the respective ministries or agencies. Since the original publications, which describe the systems of the mentioned countries, were gathered, further research was held in the cited literature of the above publications. In addition, online search engines such as Scopus, Google Scholar, WorldWideScience, ScienceDirect, and ResearchGate were used, with the use of the following keywords: "fire danger", "fire danger rating systems", "fire danger indices", "fire ignition probability", "fire danger and remote sensing", "fire danger and drought", and "forest fire danger rating systems", among others. The research was conducted during an eight-month period lasting until July 2022, while the consulted sources were scrutinized according to the following steps: (1) the titles of the studies were compared with the above keywords; (2) those that matched were examined by their respective abstract; and (3) those whose abstracts fulfilled the selection criteria mentioned above were included. Moreover, filters such as "natural caused fires", "risk assessment", and "year of publication" were used.

Systems and indices included in the current study were divided into two groups: (1) the ad hoc fire systems indices; and (2) the indirect indicators. The first one consists of all the systems developed exclusively for fire danger estimation gathered based on geographical criteria, while the second one contains indices that have been proven to be to a certain extent related to fire danger estimation and are divided into drought or moisture presence and into remote sensing indices. All systems and indices involve three major procedures: (1) the collection of the input data; (2) the computational procedure; and (3) the outcome categorization in danger classes. These three procedures were identified and extracted from the collected studies. The first two are described in the next sections. The last one, alongside supporting material from the computational procedure in the form of tables, is included in the Supplementary Material (SM) of the present paper. Tables and sections in the Supplementary Material are cited in the manuscript with the indication "S", followed by the number of the respective table or paragraph.

All systems indices were eventually evaluated based on the cited literature. For validating the accuracy of each system index, the values of the latter were calculated for the two-month period from June–July 2022 using an ad hoc calculating package created in the Python programming language. Hence, the computed values were correlated to days with and without fire occurrences. The principles and the material gathered in the current review are expected to contribute positively to the forest fire science. All parameters not described after the presented equations are included in the Supplementary Material as Section S3. Nomenclature.

3. Results

Overall, a total of 210 studies met the inclusion criteria and were considered in the review. The selection process in numbers is presented in Figure 1. From the selected studies, a total of 63 systems indices were gathered—including modified versions—across 16 countries, as presented in Table 1.

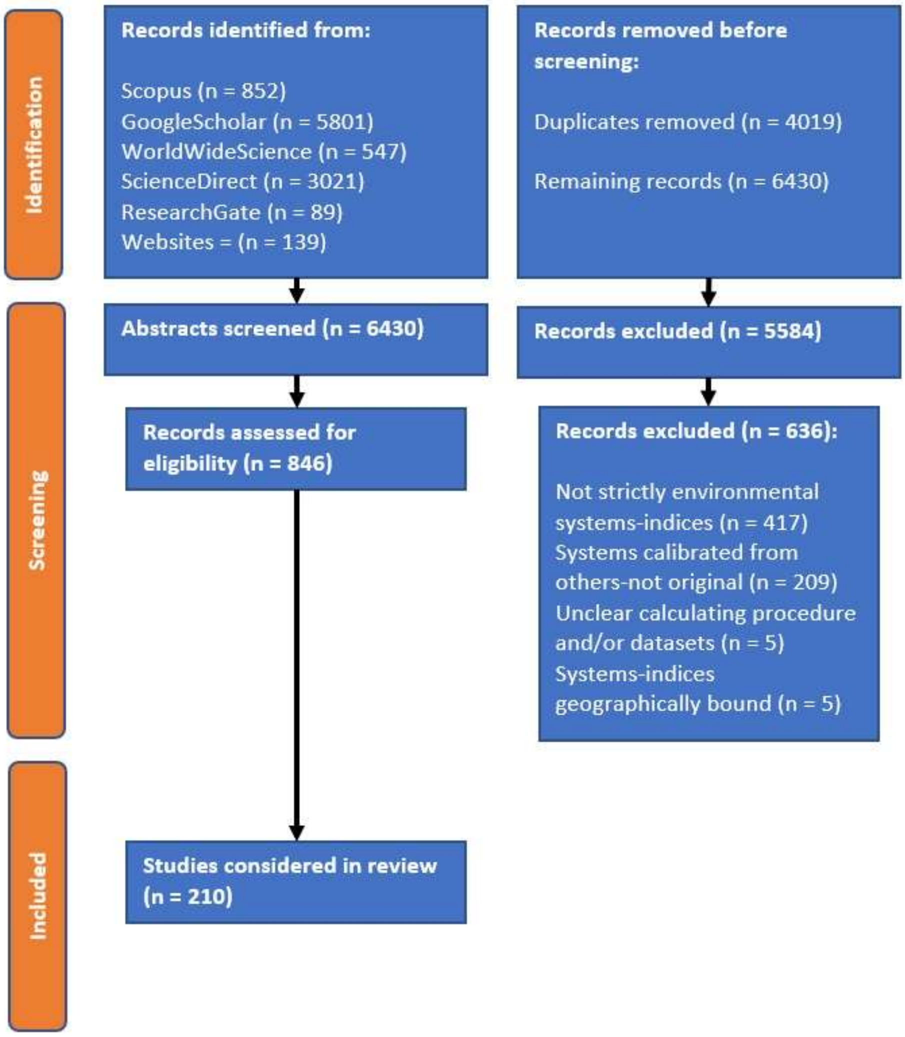

Figure 1. The selection process of consulted studies based on PRISMA 2020 flowchart for systematic reviews.

3.1. North America Fire Danger Systems and Indices

3.1.1. Canadian Forest Fire Danger Rate System

The Canadian Forest Fire Danger Rate System (CFFDRS) is a meteorologically based approach in fire danger rating developed in Canada in 1968, consisting of four subsystems: Fire Weather Index (FWI), Fire Behavior Prediction (FBP), Fire Occurrence Prediction (FOP), and Accessory Fuel Moisture (AFM) [30,51,52]. In the current study, though, only the FWI system will be considered, as it is related to fire ignition probability. The FWI system comprises six modules: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI), Buildup Index (BI), and Fire Weather Index (FWI) [30,53]. The three moisture codes refer to the moisture levels of three different fuel type categories, respectively, depending on fuel weight and fuel layer depth, while the two following indices are intermediate products that are related to fire spreading and total available fuel accordingly and produce the FWI [30,52,54–56]. The final index, FWI, is a general measure of fire danger representing potential fire-line intensity [56–58]. The calculation of all FWI system components is complex, as a total of 30 computation steps lead to the final output [59].

Depending on FWI values, six danger classes were defined in the original publication [30] as displayed in Table S1. However, when FWI is used in other countries, classes are redefined based on local calibrations [47,60–64].

3.1.2. National Fire Danger Rating System

The National Fire Danger Rating System (NFDRS), developed in 1972 [29] and revised in 1978, 1988 [14,65,66], and 2016, is the USA fire danger rating approach. It is designed to be scientifically based, applicable across the USA, adaptable, and inexpensive in operating terms [27]. The NFDRS uses meteorological as well as fuel moisture and topographical inputs, while a series of equations and calculations lead to six hourly output components: Spread Component (SC), Energy Release Component (ERC), Burning Index (BI), Ignition Component (IC), Human- and Lightning-Caused Fire Occurrence Index, and Fire Load Index [65,67,68]. The first three indices are based on combustion physics [69] and correspond to fire behavior characteristics, while the remaining indices provide an estimation on fire danger rating [29,65]. In the computation procedure, in which computer programs such as "AFFIRMS" and "FireFamily" or nomograms can be utilized, land slope is divided into three classes and fuel types into five, while nine fuel models are implemented in the system [29,65,70–73].

The NFDRS has various outputs; therefore, the categorization of fire danger rating can be estimated through the evaluation of different aspects of the system's components. In the current study, fire danger rating (Table S2) was produced based on the fire characteristics charts.

Table 1. Environmental fire danger rating systems indices.

No	Systems Indices	Origin	Publications
Ad hoc Fire Danger Rating Systems			
North American			
1	CFFDRS	Canada	[30,51,55,56,59]
2	NFDRS	USA	[29,65–67]
3	Fosberg	USA	[74,75]
4	Fosberg +	USA	[76]
5	BEHAVE	USA	[69,73,77,78]
6	CBI	USA	[79]
7	HDWI	USA	[80]
8	LASI	USA	[81]
Southern Hemisphere			
9	FFDI	Australia	[28,82,83]
10	GFDI	Australia	[28,82,84]
11	FFBT	Australia	[85,86]
12	SFDI	Australia	[87,88]
13	LFDI	S. Africa	[89,90]
14	FMA	Brazil	[91]
15	FMA+	Brazil	[92]

Table 1. *Cont.*

No	Systems Indices	Origin	Publications
16	IRM	Argentina	[93]
17	RF	Brazil	[94]
18	EPI	Brazil	[95]
19	PEI	Brazil	[95]
Mediterranean			
20	r (Orieux)	France	[96]
21	I87	France	[97]
22	Numerical	France	[98]
23	Lourenco	Portugal	[99]
24	Lourenco_m100	Portugal	[99]
25	Lourenco_f	Portugal	[99]
26	Ifa	Portugal	[100,101]
27	ICONA	Spain	[102]
28	CFS	Italy	[103]
29	IREPI	Italy	[104]
30	IFI	Italy	[105,106]
31	DMRIF	Tunisia	[107]
North Eurasian			
32	AI	Sweden	[108]
33	BI_t	Germany	[109]
34	I_{Br}	Germany	[110]
35	TLI	Russia	[111]
36	NI	Russia	[112]
37	mNI	Russia	[113]
38	Zhdanko	Russia	[114]
39	M68	Germany	[113]
40	mM68	Germany	[113]
41	DW	Finland	[115]
Indirect Indicators			
Drought–Moisture			
42	MDI	USA	[116]
43	KBDI	USA	[117]
44	SDI	Australia	[118]
45	PDSI	USA	[119]
46	RDI	Greece	[120]
47	CWD	USA	[121]
48	VPD	USA	[122]
49	DI	France	[123,124]
Remote Sensing			
50	NDVI	USA	[125]
51	RG	USA	[31]
52	VG	USA	[31]
53	NDWI	USA	[126]
54	NDWI_m	USA	[127]
55	NDII_6	USA	[128]
56	NDII_7	USA	[128]
57	NMDI	USA	[129]
58	SAVI	USA	[130]
59	EVI	USA	[130]
60	VARI	USA	[131]
61	FPI	USA	[70,132]
62	FPI_m1	USA	[133]
63	FPI_m2	USA	[61,134]

3.1.3. Fosberg and Modified Fosberg Indices

Fosberg developed an index supplemental to the NFDRS based on wind speed and equilibrium moisture content [74–76]. The basic equation, in SI units, is given below:

$$\mathrm{FFWISI} = \frac{\eta}{0.3002}\left[1 + \left(\frac{w}{1.690344}\right)^2\right]^{0.5} \quad (1)$$

where $FFWI_{SI}$ is Fosberg index (SI units), η is a factor related to equilibrium moisture, and w is wind speed (km/h). The index value categorization is shown in Table S3 [76,135].

Since the original index ignores precipitation, a modified version was proposed by Goodrick [76], which includes a drought index developed by Keetch and Byram [117]:

$$\mathrm{FAF} = 0.000002\ \mathrm{KBDI}^2 + 0.72 \quad (2)$$

where FAF is a correction function, and KBDI is the Keetch and Byram drought index. The improved formula of Fosberg index can be computed as follows:

$$\mathrm{FFWI_m} = \mathrm{FAF} \cdot \mathrm{FFWI_{SI}} \quad (3)$$

The original form of the Fosberg index is described in paragraph S2.1 in Supplementary Material, including the calculation of the other parameters.

3.1.4. BEHAVE System

BEHAVE is a system for evaluating fire potential that uses the same mathematical model as NFDRS although the equations differ as well as the input parameters, which can vary according to the available information, while the concept of BEHAVE focuses on fire behavior prediction rather than fire danger rating [77,136,137]. It consists of two subsystems, one for fuel modeling—in which 13 fuel types are introduced—and one for fire prediction, in which Rothermel's models are deployed alongside Byram's fire intensity [57,69,78].

3.1.5. Chandler Burning Index

Chandler proposed a simple index as a function of air temperature and relative humidity that estimates fuels ignitability and is calculated as follows [79]:

$$\mathrm{CBI_d} = \left[(104.5 - 1.373\mathrm{RH} + 0.54\mathrm{T})124 \cdot 10^{-0.0142\mathrm{RH}}\right]\frac{1}{60} \quad (4)$$

$$\mathrm{CBI_m} = \left\{[(110 - 1.373\mathrm{RH}) - 0.54(10.2 - \mathrm{T})] \cdot 124 \cdot 10^{-0.0142\mathrm{RH}}\right\}\frac{1}{60} \quad (5)$$

where CBI_d and CBI_m are daily and monthly, respectively, Chandler Burning Indices. For calculating CBI_m, average values of dry bulb air temperature T (in °C) and relative humidity RH (%) over a 30-day period are required. The categorization of the index is presented in Table S4.

3.1.6. Hot-Dry-Windy Index

A simple index combining air temperature, relative humidity, and wind speed was developed in 2018 in the USA and named the Hot-Dry-Windy Index (HDWI). It can be computed with the following equation [80,138]:

$$\mathrm{HDWI}\left(\frac{\mathrm{km}}{\mathrm{h}}\right) = \frac{\mathrm{W}_{max}\ \Delta \mathrm{e}_{max}}{3.6} \quad (6)$$

where W_{max} is the maximum wind speed (m/s), and Δe_{max} is the maximum vapor pressure deficit (hPa) on daily basis, and the factor 3.6 is needed for conversion to SI units. The HDWI has been evaluated for a short number of incidents. A better accuracy for severe fire occurrences than the following LASI index was observed, so it has also been proposed to replace the latter one in the USA; however, further analysis is required, as it is presumed to perform poorly in thunderstorm-caused fires [80,138–140]. The higher the index values, the higher the fire danger.

3.1.7. LASI Index

The Lower Atmosphere Stability Index (LASI) is based on the atmospheric stability conditions and severe fires of a 20-year period [81]. Haines divided the USA into three climatic zones based on average elevation, where the LASI index is applied differently, as shown in Table S5 [81,141–143].

The LASI index is significantly different from all other indices analyzed in the current study, as it uses dry bulb air temperature values from two different atmospheric pressure levels based on elevation as well as the difference between dry bulb air temperature and dew point temperature on a third level, which is either the first or the second one, according to Table S5. LASI has been proven to perform well in diverted climatic regions of the world and has a very simple computational process [143–148]. Nevertheless, the low availability of the input data from a typical meteorological station limits the wider usage of LASI, while the absence of wind speed and drought factors substitutes LASI as a supplemental index for forest fire danger rating.

3.2. South Hemisphere Fire Danger Systems and Indices

3.2.1. Australian Systems and Indices

Two major fire danger rating systems were developed in Australia: McArthur Fire Danger Meters and Forest Fire Behavior Tables [28,82]. The first system was designed for Eastern Australia in the 1960s and has undergone since then several revisions, with the final versions being Mark 5 (FFDI) for forest fires and Mark 5 (GFDI) for grassland fires. The second was designed for western Australia in 1980s and is based on tables that predict fire behavior based on fuel characteristics and types of six dominant tree species [85,86]. These systems were produced based on empirical data from experimental fires in the Australian wildland [28,85]. The following equations can be used for the computation of the systems mentioned above [82]:

$$\mathrm{FFDI} = 2e^{(-0.45 + 0.987\ln(\mathrm{DF}) - 0.0345\mathrm{RH} + 0.0338\mathrm{T} + 0.0234\mathrm{W})} \tag{7}$$

where DF is a drought factor calculated as in paragraph S2.2 in Supplementary Material [82]. Accordingly, grassland fire danger indices (Mark 5) can be calculated based on paragraph S2.2 in Supplementary Material [82–84].

Eventually, the forest fire behavior tables (FFBT) system was designed to be deployed in a different manner than the previous systems, based on parameters provided in the aforementioned tables [85]. Nevertheless, a set of 72 equations was developed in the 1990s, from which the basic ones that describe the final index are displayed in paragraph S2.2 in Supplementary Material [99,102]. The categorization of the indices' danger classes analyzed above is based on the fire danger rating and displayed in Table S6; hence, the rest of FFBT output categorization is omitted [84,149,150].

In 2009, due to the complexity of the established systems in Australia, Sharples developed a computationally simple index. Firstly, a simple fuel moisture index was introduced, validated in the Australian eucalypt forests, and given by the following equation [87]:

$$\mathrm{SFMI} = 10 - 0.25(\mathrm{T} - \mathrm{RH}) \tag{8}$$

where SFMI represents Sharples' fuel moisture index.

Secondly, embodying SFMI, Sharples developed a fire danger index taking into account wind speed values, according to the following equation [88]:

$$\mathrm{SFDI} = \frac{\max(\mathrm{Wo}, \mathrm{W})}{\mathrm{SFMI}} \tag{9}$$

where SFDI (Equation (9)) stands for Sharples' fire danger index; Wo is set to 1 km/h in order to avoid zero values. The categorization of the index danger classes is presented in Table S7 [88].

3.2.2. Lowveld Fire Danger Index

Lowveld Fire Danger Index (LFDI) was developed in South Africa based on the Angstrom and the Canadian Forest Fire Danger Rating Systems and has been the official system used in the country, with the computational procedure being the following [89,90,151]:

$$\text{LFDI} = (\text{BI} + \text{WF})\ \text{RCF} \tag{10}$$

where LFDI is the Lowveld Fire Danger Index, BI is the Burning Index, WF is the Wind Factor, and RCF is the Rain Correction Factor. BI is related to the Angstrom index (with $R^2 = 0.99$), while it has been proven to be accurate in Greece—a typical Mediterranean country with long fire seasons [151]. The components of the index are presented in paragraph S2.3 in Supplementary Material, while the fire danger classes of the index are presented in Table S8.

3.2.3. Formulas of Monte Alegre

Megafires occur frequently in the tropical forests in the greater Amazon area; hence, a significant number of indices have been proposed and applied in Latin America Countries, mostly at the regional level [152,153]. Thus, a plethora of indices has been in use currently in Latin America. The first one, FMA, is a simple index that combines the number of days without any precipitation and relative humidity values, as attested by the following equation [91,153–155]:

$$\text{FMA} = \sum_{i=1}^{n} \frac{100}{RHi} \tag{11}$$

where *RH* stands for relative humidity on day *i*; *n* is the total amount of days without rain greater than 12.9 mm. However, in the case of rain between 2.5 and 12.9 mm, the FMA index must be reduced, as displayed in Table S9.

The FMA formula takes into account only two of the core meteorologic parameters; hence, an alteration has been proposed in order to include wind speed in the computational procedure [92,153–155]:

$$\text{FMA}^{+} = \sum_{i=1}^{n} \left(\frac{100}{RHi}\right) \text{e}^{(0.04\text{W})} \tag{12}$$

The categorization of danger classes of both indices is shown in Table S10.

3.2.4. Rodriguez–Moretti Index

The Rodriguez–Moretti Index (IRM), elaborated in the regions of Andean and Patagonia, combines the four basic meteorological components: dry bulb air temperature, wind speed, relative humidity, and days without any rain greater than 2 mm [93,153,156,157]. Each of the four components is converted to input values using respective tables, as summarized in Table S11, according to the following equation [93,153,156,157]:

$$\text{IRM} = \text{Ti} + \text{RHi} + \text{Wi} + \text{Ri} \tag{13}$$

where Ti is temperature index, RHi is relative humidity index, W is wind speed index, and Ri is rainless days. The fire danger classes of the index are presented in Table S12 [93,153,156,157].

3.2.5. Risco do Fogo Index

The Risco do Fogo (RF) was developed by the Brazilian "Instituto Nacional de Investigaciones Espaciales" (INPE) based on simple meteorological inputs and vegetation type [94,157–159]. However, RF requires precipitation data for a period of 120 days in advance of the day of interest in order to estimate a series of respective factors [94,157–159].

The equations describing the precipitation factor—which is of great importance in fire danger estimation for the current index—the period of drought, as well as the other components of the index are presented in paragraph S2.4 in Supplementary Material and in Table S13.

$$\mathrm{RF} = \mathrm{RF_o} \cdot \mathrm{FLAT} \cdot \tag{14}$$

where FLAT and FELV are latitude and elevation factors, accordingly, and RF is the final fire risk (Risco do Fogo). The categorization of the index danger classes is displayed in Table S14.

3.2.6. Evaporation-Precipitation Indices

Two indices related to evaporation and precipitation are described in the current section. The first one is based on the division of the two parameters, while the second one is based on the respective difference [93,95,160]:

$$\mathrm{EPI} = \sum\nolimits_{i=1}^{t} \left(\frac{E_i}{P_i}\right) \tag{15}$$

where EPI is the evaporation divided by precipitation index, E is evaporation (mm), and t is the number of days since the start of the calculations. Respectively, the second index is computed as follows [93,95,160]:

$$\mathrm{PEI} = \sum\nolimits_{i=1}^{t} (P_i - E_i) \tag{16}$$

where PEI is the precipitation subtracted with evaporation. Both indices are cumulous, and their calculations follow the restrictions shown in Table S15 [95,160]: The higher the EPI index values, the higher the fire danger, while the lower the PEI index values, the higher the fire danger [95,154,155,160,161].

3.3. Mediterranean Indices

3.3.1. Orieux Index

In recent decades, forest fires have been on the rise across the Mediterranean, a region that has been indicated as severely vulnerable to climate change impacts, including increased forest fire season duration [162–164]. Moreover, the largest percentage of human-caused fires (95%) worldwide has been reported in the Mediterranean [165,166]. Hence, a great number of systems have been developed and used although other indices under calibration, such as the FWI from CFFDRS and FFDI, are currently preferred to be used [63,105,166].

The first of the Mediterranean indices presented here is the one developed in France by Orieux and is based on the exponential decrease of soil water reserve as well as wind speed values. The calculation of the index requires the estimation of the potential evapotranspiration through the Thornthwaite equation [96,167,168]. A maximum water reserve value of soil is considered to be 150 mm and represents the starting point of the index calculation, as the following equation suggests [96]:

$$\mathrm{r} = \mathrm{R} \cdot \mathrm{e}^{\left(-\frac{\Sigma \mathrm{ETP}}{\mathrm{R}}\right)} \tag{17}$$

where r is the daily value of soil water reserve (which represents Orieux index), R is the maximum value of r equal to 150 mm, and ETP is the potential evapotranspiration computed through Thornthwaite's equation as in paragraph S2.5 in Supplementary Material and Table S16 [119,167,169].

The Orieux index is cumulative; thus, the previous day ETP is needed for present-day calculations. If precipitation occurs, the index increases although in the original publication [96], the method of applying the rainfall event effects is not clarified. Index categorization classes can be estimated as presented in Table S17.

3.3.2. Carrega's I_{87} Index

Another index developed in France as well, by Carrega [97,170], embodies the soil water reserve index as proposed by Orieux [96] alongside superficial water reserve, temperature, relative humidity, and wind speed. Index I_{87}, which is an amelioration of I_{85}, was proposed by Carrega [96], and it additionally includes temperature and superficial water reserve and can be calculated as follows [170]:

$$I_{87} = \frac{\max(10, T)W \cdot C}{RH \cdot r_s\sqrt{r}} \tag{18}$$

where T is dry bulb air temperature in °C, W is wind speed in m/s, RH is relative humidity (%), C is a phenological coefficient that corresponds to 200 in summer and winter and 100 in autumn and spring, r is Orieux water reserve saturated at 150 mm, and r_s is superficial water reserve saturated at 10 mm and computed using Thornthwaite's equation, as in paragraph S2.5 in Supplementary Material.

Carrega's index is cumulative as well; hence, the previous-day evapotranspiration is needed in the computation of current-day parameters. In case of a rain event, the values of soil water reserve and superficial reserve must be augmented by the amount of rain, while the second reserve must be further increased by 1 mm if dew occurs during night or 2 mm if the dew is strong [170]. The categorization of Carrega's index is not represented clearly in the original publication, where a very high danger corresponds to values greater than 200.

3.3.3. Numerical Index

The third index, called the Numerical Index and developed by Drouet and Sol in southern France, is based on the product of soil water reserve, wind speed, and false relative humidity, while other meteorological factors, such as temperature and cloud coverage, are used although considered less important [98,171,172]. The estimation of the index undergoes the following procedure:

$$\text{Numerical Index} = 25 - \frac{(FHR \cdot C_{res} \cdot C_{vent})}{15} + A \tag{19}$$

where FHR is the false relative humidity, C_{res} is the coefficient of soil water reserve, C_{vent} is the coefficient of wind, and A is a correction coefficient. These parameters are computed as described in paragraph S2.6 in Supplementary Material [173,174]. The fire danger classes are shown in Table S18.

3.3.4. Portuguese Indices

Another index developed in the Mediterranean is the Portuguese index. It was developed by the Portuguese Meteorological and National Institute by modifying the Nesterov index (presented in a later section). The Portuguese index is an estimation of atmospheric conditions at the fuel layer and consists of three indicators [100,101]: an ignition index, a rain coefficient, and a wind speed coefficient. The final index can be estimated according to the following equations [100,101,175]:

$$Ifa_i = I_i + Ia_{(i-1)} + CW \tag{20}$$

where Ifa_i is the Portuguese Index on day i, I_i is the ignition index, $Ia_{(i-1)}$ is a variant of the Nesterov Index, and CW is a wind coefficient. The calculations can be found in paragraph S2.7 in Supplementary Materialand and Table S19.

Finally, Ifa_i and $Ia_{(i-1)}$ are re-estimated according to tables presented in the original publication as well as the Swiss Federal Institute's fire weather danger wiki [176], while the danger classes are shown in Table S20.

Lourenço [99]—one of the two developers of the Portuguese Fire Danger Index—describes five simple fire danger indices that require only two to three of the basic meteorological parameters. These indices are described in the following equations:

$$\mathrm{LFDRI} = \frac{\mathrm{T}}{\mathrm{RH}} \tag{21}$$

where LFDRI stands for Lourenço's fire danger index, T is dry bulb air temperature, and RH is relative humidity. Three variations of Lourenço's fire danger index (LFDRImax, LFDRIm, and LFDRIm100) have been documented, which use the maximum and minimum values of temperature and the relative humidity, respectively, as well as wind speed values (see paragraph S2.7 in Supplementary Material). The final index provided by Lourenço combines meteorological data from the day of interest plus the sequent day's forecast, as given below:

$$\mathrm{LFDRIf} = \left\{ \frac{Ti}{RHi} + \frac{Wi}{100} + \left\{ [2(Tj - Ti) + (RHi - RHj) + (Wj - Wi)] \frac{1}{100} \right\} \right\} R \tag{22}$$

where LFDRIf is Lourenço's fire danger index for forecast, i represents current day, j the next day, and R is a risk factor based on each region's historical profile in fires, as shown in Table S21 with the categorization of the LFDRI indices fire danger classes [99].

3.3.5. ICONA Index

Another method for predicting forest fire danger rating, in the Mediterranean, was developed in 1993 in Spain [102] although a calibrated and enhanced version of the Canadian FWI is currently in operation in the country [177]. The ICONA index is based on fine fuel moisture content and wind speed, embodying the parameters for fuel modelling that the BEHAVE system utilizes [78]. The calculation process depends on tables provided by the system [102], and the terms and parameters have been translated as presented in paragraph S2.8 in Supplementary Material. The original publication defines four danger classes, as presented in Table S22 [102].

3.3.6. Italian Indices

There are two major indices used in continental Italy: the first one has been applied mostly in the Mediterranean part of Italy (CFS—Italian Fire Danger Index) and is based on McArthur's meters, while the second one (IREPI) was developed especially for the Alpine regions [103,104]. The Italian Fire Danger Index consists of both equations and tables, where simple meteorological data are inserted. The computational process is presented in paragraph S2.9 in Supplementary Material [103,175]. The Italian Fire Danger Index main equation is shown below:

$$\mathrm{CFS} = 3.9\mathrm{Ar}2^{(0.048\mathrm{T} - 0.051\mathrm{RH} + 0.033\mathrm{W})} \tag{23}$$

where Ar is a parameter estimated as given in paragraph S2.9 in Supplementary Material. The index is cumulative, as the previous day's soil water deficit is needed, while the categorization can be estimated as displayed in Table S23 [178,179].

The second index, designed for the Italian Alps, is based on the relationship of potential and daily evapotranspiration and is called "Indice di Riduzione Evapotranspirazione per il Pericolo d'Incendio" (IREPI). The following equation can be used for the IREPI estimation [104,180]:

$$\mathrm{IREPI} = \left(\frac{(\mathrm{ETP} - \mathrm{ETR})}{\mathrm{ETP}} \right) 100 \tag{24}$$

where ETP is the potential evapotranspiration, and ETR the real evapotranspiration in mm per day. There is a plethora of equations and methods in order to compute ETR and ETP, as are presented analytically in Xiang et al. [181] and McMahon et al. [182]. As this difference increases, the fire danger decreases.

A third index designed for Mediterranean vegetation characteristics is operational in Sardinia, named the Integrated Fire Index or Ichnusa Fire Index (IFI), and consists of four components [105,106,183]. Two versions of the index have been documented; thus, both will be presented in the current study:

$$\text{IFI} = \text{DC} + \text{FC} + \text{MC} + \text{TC} \tag{25}$$

where DC is Drought Code indicating the evapotranspiration rate, FC is Fuel Code, MC is Meteo Code, and TC is Topological Code.

$$\text{IFI}' = \text{DC} + \text{FC} + \text{MC} + \text{R} \tag{26}$$

with R being the code for solar radiation, replacing the TC parameter. The calculation of the above codes is analyzed in paragraph S2.9 in Supplementary Material. The categorization of the index is based on five danger classes (Table S24) after the normalization of the index, a process not clearly described in the original publication [106].

3.3.7. Tunisian Index

DMRIF is a simple index used in Tunisia, which requires a limited number of weather parameters [107,184]. According to the number of days since last rainfall event, there are two cases:

$$\text{DMRIF} = -131.7\text{r} + 5.9\text{W} + 26.8\text{N}_\text{d} + 1.4\text{T}_\text{max} - 32.8\text{Q}, \text{ if } \text{N}_\text{d} > 6 \tag{27}$$

$$\text{DMRIF} = -26.3\text{r} + 4.6\text{W} + 0.5\text{T}_\text{max}, \text{ if } \text{N}_\text{d} \leq 6 \tag{28}$$

where r represents the soil water reserve (mm), which can be estimated according to Thornthwaite equation; W defines wind speed (m/s); N_d is the number of days since the last rainfall event; T_{max} is maximum dry bulb air temperature (°C); and Q is the amount of precipitation (mm). The index categorization differs for each case, as shown in Table S25 [107,185].

3.4. Northern Eurasian Indices

3.4.1. Angstrom Index

Forest fires are rapidly increasing in the temperate and boreal forests of northern Europe and Russia as well due to climate change, among other causes [37,186–188]. Several indices have been developed in the greater area, which have been also deployed in diverted climatic zones [64,68,155,189].

One of the simplest but also highly effective indices in the respective literature is the index developed in Sweden by Angstrom [152,153]. The index is calculated based on the following equation [79,108]:

$$\text{AI} = \frac{\text{RH}}{20} + \frac{27 - \text{T}}{10} \tag{29}$$

where RH is relative humidity (%), and T is temperature (°C), both measured at 13:00 local time. The index categorization is in line with Table S26 [79,108].

3.4.2. Baumgartner Index

The Baumgartner index was developed and destined to be deployed in Bavaria although some findings indicate that its suitability in the area is limited [190]. The index relies directly on precipitation and indirectly on temperature, wind speed, net solar radiation, elevation, and relative humidity of five days in advance of the current one, according to the following equation [68,109]:

$$\text{BIt} = \sum_{i=1}^{5} (\text{ETP}_{\text{i}-1} - \text{P}_{\text{i}-1}) \tag{30}$$

where BIt is Baumgartner Index for day t, ETP is potential evapotranspiration calculated by Penman equation [191], and P is precipitation in mm. The respective categorization, which excludes winter months fire danger, is shown in Table S27.

3.4.3. Bruschek Index

Another index developed in Germany, called Bruschek Index, that uses simple meteorological data can be computed by the following equation [110,192]:

$$I_{Br} = \frac{\sum_{i=vs}^{ve} sdi}{\sum_{i=vs}^{ve} Pi} \quad (31)$$

where I_{Br} is Bruschek Index, sdi is a parameter that equals 1 whether daily dry bulb air temperature is equal or greater than 25 °C and 0 in all other cases on day i, Pi is the precipitation depth on day i, vs is the starting period of vegetation green-up (the 1st of April), and ve is the end period (the 30th of September). The higher the index values, the higher the fire danger.

3.4.4. Telicyn Logarithmic Index

Another index mostly used in the tropical forests of Latin America—although developed in the Soviet Union [111]—is the Telicyn logarithmic Index (TLI), which requires simple meteorological inputs. The computational procedure is based on the following equation [153–155]:

$$TLI = \sum_{i=1}^{n} \log 10(Ti - Tdew, i) \quad (32)$$

where Ti is the dry bulb air temperature on day I; Tdew,i is dew point temperature on day i; n is the number of days without rain greater than 2.5 mm; and log10 is the logarithm on base 10. When the rainfall depth exceeds 2.5 mm, the index is set to zero. In line with the Monte Alegre formulas, the index is cumulative, requiring values of the previous day. The categorization of the index can be concluded from Table S28 [92,160,193].

3.4.5. Nesterov, Modified Nesterov, and Zhdanko Indices

The index of Nesterov—amongst the most widely used [47,68,101,105,112,155]—was developed in the Soviet Union. The index uses the dry bulb air temperature and dew point temperature as well as the number of days with precipitation depth less than 3 mm, according to the following equation [47,79,112]:

$$NIt = \sum_{i=1}^{t-1} (Ti - Tdew, i) Ti \quad (33)$$

where NI_t is the Nesterov index on day t. The meteorological data must be recorded at 15:00 local time. Two modified versions of Nesterov index were proposed by Käse and Zhdanko, as in paragraph S2.10 in Supplementary Material and in Table S29 [113,114,186]. The categorization of the Nesterov indices is displayed on Table S30 [194,195]. However, no categorization of the Zhdanko index was found in the respective literature although the index is similar to Nesterov but with much lower values.

3.4.6. M68 and Modified M68 Indices

M68 was developed by Käse in east Germany based on the same principle as the Nesterov index; however, three coefficients are implemented representing corrections related to precipitation, snow coverage, and vegetation condition, as presented below [113,192,196]:

$$M68_t = \sum_{15\ Febr}^{30\ Sept} (Tt - 10) \Delta e_t, \text{ (without coefficients)} \quad (34)$$

The calculations of the modified versions of M68 index are presented in paragraph S2.11 in Supplementary Material and Table S31. The categorization of the M68 and the modified M68 are displayed in Tables S32 and S33.

3.4.7. Finnish Fire Index

The Finnish Fire Index (FFI) is based on the calculation of volumetric moisture content changes, and most of the parameters can be computed according to Allen et al. [173] and Monteith [197]. The FFI relies on three components [115,198,199]:

$$\mathrm{DW} = \mathrm{E_{pot}} \cdot \mathrm{DE} + \mathrm{P_i} \tag{35}$$

where DW is the volumetric moisture content change of the total surface layer, Epot is the potential evaporation according to Penman and Monteith equation, DE is the drying efficiency, and P_i the precipitation depth in mm remaining in the surface layer. These three components can be calculated as in paragraph S2.12 in Supplementary Material [199]. The value of DW can be calculated as well as the fire danger class according to Table S34 [64,199].

3.5. Drought–Moisture Indices

3.5.1. Munger Drought Index

The first index, proposed in 1916 by Munger, is based on the number of consecutive days with precipitation height less than 1.27 mm and has been proven to be efficient for short-time drought periods [116,200]:

$$\mathrm{MDI} = 0.5 \cdot \mathrm{d}^2 \tag{36}$$

where MDI represents Munger's Drought Index; d is the number of consecutive days with rain height less than 1.27 mm. The higher the index value, the higher the fire danger is.

3.5.2. Keetch–Byram Drought Index

The drought index proposed by Keetch and Byram (KBDI) is one of the most used in fire danger rating systems. It is based on the next principles: the rate of moisture loss dependent on vegetation density, vegetation and rainfall have an exponential relationship, evapotranspiration determines the rate of soil's moisture loss—which is depleted with time exponentially, and an arbitrary layer depth of 8 in. (~20 cm) of soil capacity is arbitrarily used [47,81,82,117,201]. The following equations can be used for KBDI calculation:

$$\mathrm{KBDI_t} = \mathrm{Q} + \left[(800 - \mathrm{Q})\left(0.968\mathrm{e}^{0.0486(1.8\mathrm{T}+32)} - 8.3\right)\mathrm{dt}\right] \frac{10^{-3}}{1 + 10.88\mathrm{e}^{\left(\frac{-0.0441^{P_a}}{25}\right)}} \tag{37}$$

The components of the KBDI can be computed according to paragraph S2.13 in Supplementary Material as well as the original form of the KBDI equation [202,203]. The index categorization can be concluded according to Table S35 [117,204]. The KBDI index has been criticized for underestimating soil drying or wetting rates, especially in the critical phase between spring and summer, while it ignores the contribution of wind [47,118,205].

3.5.3. Soil Dryness Index

In order to solve the KBDI's inaccuracies, Mount developed the Soil Dryness Index (SDI), which embodies a different calculation approach for interception and runoff components into the soil–moisture deficit relationship [118,205,206]. The computational procedure is analyzed below:

$$\mathrm{SDI_t} = \mathrm{SDI_{t-1}} - \mathrm{P_{net}} + \mathrm{ET} \tag{38}$$

where SDI represents Soil Dryness Index on day t, P_{net} is the net precipitation, and ET is the evapotranspiration. The latter two components can be estimated based on Table S36 and paragraph S2.14 in Supplementary Material [118]. The SDI categorization for fire danger is described in Table S37 [205].

3.5.4. Palmer Drought Severity Index

One of the most-used drought indices in the USA is the Palmer Drought Severity Index (PDSI) developed in 1965; this index has also been associated with forest fire danger rating estimation [207–209]. The index relies on the hydrologic balance of water supply and loss—using historical drought data—dividing soil into layers with different water storage capacity, according to the following formulas [207–209]:

$$\mathrm{PDSI_i} = 0.897\mathrm{PDSI_{i-1}} + \frac{\mathrm{z_i}}{3} \tag{39}$$

where $\mathrm{PDSI_i}$ is Palmer's drought severity index on month i, and Z is the current moisture anomaly on the same month, as described in detail in paragraph S2.15 in Supplementary Material and Table S38 [173,207–212].

Although PDSI is the most broadly used drought index in the USA, there are some skeptical reviews considering the evapotranspiration calculation approach, the simplification method used for potential runoff and recharge delay, the ignorance of freezing conditions, the monthly basis estimation of the index, as well as the arbitrary subdivision of drought classes [208,213,214]. The index categorization is presented in Table S39 [207].

3.5.5. Reconnaissance Drought Index

A drought index embodying cumulative precipitation and potential evapotranspiration is the Reconnaissance Drought Index (RDI), and its three versions are as described below [120,215]:

$$\mathrm{RDIk} = \frac{\sum_{j=1}^{k} P_j}{\sum_{j=1}^{k} ETP_j} \tag{40}$$

where $\mathrm{RDI_k}$ is the index value for month k, P_j is the precipitation on month j, and ETP_j is the potential evapotranspiration on month j. The two other versions of the index are presented in paragraph S16 in Supplementary Material. The categorization of the last version of the index is presented in Table S40.

3.5.6. Climatic Water Deficit and Vapor Pressure Deficit

Another two indicators of water presence in the vegetation and in the air are climatic water deficit and vapor pressure deficit, respectively, with the latter already being mentioned. These indices have been directly correlated to some extent with fire danger, while they are included in other systems as well [3,121,122]:

$$\mathrm{CWD} = \mathrm{ETP} - \mathrm{ETR} \tag{41}$$

$$\Delta\mathrm{e} = \mathrm{E_{sat}} - \mathrm{Eact} = 0.6108\mathrm{e}^{\frac{17.27\mathrm{T}}{\mathrm{T}+237.3}}\left(1 - \frac{\mathrm{RH}}{100}\right) \tag{42}$$

where CWD is Climatic Water Deficit; ETP and ETR represent potential and real evapotranspiration, respectively.

3.5.7. Darcy's Law

Although Darcy's law describes the flow of a fluid through a porous medium and was basically developed to describe the flow of groundwater, a hydraulic corollary has been developed based on this law for the estimation of the possibility of a certain plant surviving harmful conditions, such as drought, wildfires, and pest attacks [123,124]. The equation is strongly related to plants physiology as well as meteorological parameters, according to the subsequent formula [124]:

$$\mathrm{DBI} = \frac{\mathrm{A_s} \cdot \mathrm{K_s}(\psi_\mathrm{s} - \psi_\mathrm{L})}{\mathrm{h} \cdot \eta \cdot \mathrm{A_L} \cdot \Delta\mathrm{e}} \tag{43}$$

where DBI is the Darcy-law-based index; A_s is the cross-sectional area of the conducting sapwood in cm^2 that has to be measured on field; K_s is the specific conductivity of the sapwood that has to be measured on field; ψ_s, ψ_L are soil and leaf water potential, respectively; h is the plant height that has to be estimated by field measurements or through remote sensing techniques; η is water viscosity that can be estimated through tables related to fluid mechanics [216]; A_L is the average leaf area that can be estimated or measured; Δe is vapor pressure deficit. The ψ_s and ψ_L can be calculated as in paragraph S2.17 in Supplementary Material [217,218]. Darcy's law requires a significant amount of field measurements, while it refers to a single tree, meaning that average values have to be inserted for vegetated areas—requiring similar plant types.

3.6. Remote Sensing Indices

3.6.1. Normalized Difference Vegetation Index

The advance in satellite technologies alongside with the remote sensing techniques has been proven significant in the development of fire danger rating systems, as the spatial and temporal resolution of the input data as well as the output indices has followed the improvement in computational systems [219]. In the current section, some of the most used and documented indices of remote sensing related to fire danger estimation will be described.

The Normalized Difference Vegetation Index (NDVI) is one of the most used concerning this category [34,220]. The index is based on the high reflectance of vegetation's chlorophyll in the near-infrared spectrum of radiation and the respective low reflectance on red, which differentiate the healthy plants containing an important amount of chlorophyll from the water-stressed ones [125,221]. The calculation of NDVI is given below [221,222]:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}} \tag{44}$$

where NIR is the near infrared value of a pixel band (with wavelength from 0.80 to 0.90 μm), and R is the respective red one band (with wavelength from 0.63 to 0.70 μm). The NDVI has been used as a proxy of fuel moisture content and has been proven to be a reliable option when the required satellite data are available [223–230]. NDVI values are in range of −1 to 1, with positive values close to 1 showing healthy vegetation and negative values close to −1 showing water stressed vegetation.

3.6.2. Relative and Visual Greenness

The Relative and Visual Greenness are indices produced by NDVI values for long and medium periods of observations and have been used in several studies as a long- and medium-term, respectively, fuel moisture index [31,231,232] according to the following equations:

$$\mathrm{RG} = 100\left[\frac{\mathrm{NDVIo} - \mathrm{NDVImin}}{\mathrm{NDVImax} - \mathrm{NDVImin}}\right] \tag{45}$$

$$\mathrm{VG} = \frac{100}{0.66}\mathrm{NDVI_o} \tag{46}$$

where RG and VG are relative and visual greenness, respectively; $NDVI_o$ is the NDVI index with values over a two-week period of observations; $NDVI_{min}$ and $NDVI_{max}$ are the NDVI index minimum and maximum values, respectively, for historical observations. Higher index values show more water presence in the vegetation.

3.6.3. Liquid Water Presence-Based Indices

Another category of indices based on the infrared bands consists of indices enhancing the visibility of plants that contain water in liquid form, such as the normalized difference water index NDWI, the normalized Multi-Band Drought Index (NMDI), and the Normalized Difference Infrared Indices (NDII), calculated as follows [126]:

$$\text{NDWI} = \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}} \tag{47}$$

where NIR as in Equation (44) and SWIR is the shortwave infrared band (with wavelength from 1.00 to 2.50 μm). A second version—less used—is given by the following expression [127]:

$$\text{NDWI}_\text{m} = \frac{\text{G} - \text{NIR}}{\text{G} + \text{NIR}} \tag{48}$$

where G is the green band (with wavelength from 0.53 to 0.60 μm). Higher values of both indices show greater water presence. Two versions also have been utilized for NDII indices concerning the bandwidth of the SWIR wavelength [128]:

$$\text{NDII}_6 = \frac{\text{NIR} - \text{SWIR}_2}{\text{NIR} + \text{SWIR}_2} \tag{49}$$

$$\text{NDII}_7 = \frac{\text{NIR} - \text{SWIR}_3}{\text{NIR} + \text{SWIR}_3} \tag{50}$$

where NDII6 is the index using the 6th band of MODIS satellites, which is represented here by SWIR2 with bandwidth 1.628–1.652 μm; NDII7 is the index using the 7th band of the respective satellite represented by SWIR3 with bandwidth 2.105–2.155 μm. In Equations (49) and (50), NIR corresponds to the 2nd band of MODIS with a bandwidth of 0.841–0.876 μm. Finally, the NMDI uses two bands for liquid water absorption, enhancing the sensitivity to drought severity concerning both plants and soil [129]:

$$\text{NMDI} = \frac{\text{NIR} - (\text{SWIR}_2 - \text{SWIR}_3)}{\text{NIR} + (\text{SWIR}_2 + \text{SWIR}_3)} \tag{51}$$

where the proposed wavelengths are 0.860 μm, 1.640 μm, and 2.130 μm for NIR, SWIR2, and SWIR3, respectively.

3.6.4. Soil Adjusted Vegetation Index

The Soil-Adjusted Vegetation Index (SAVI) also refers to NDVI, as it was proposed as an amelioration of the latter for soil reflectance correction in sparsely vegetated areas, according to the following relationship [130]:

$$\text{SAVI} = \left[\frac{\text{NIR} - \text{R}}{\text{NIR} + \text{R} + \text{L}}\right](1 + \text{L}) \tag{52}$$

where L is a factor representing vegetation density ranging from 0 (very high vegetation density—SAVI equals to NDVI) to 1 (very low vegetation density). The output values are slightly lower than the respective NDVI ones, as for leaf area index (LAI as mentioned above) equal to 0.5 and 1, NDVI ranges from 0.24 to 0.60 and from 0.44 to 0.74, while the respective SAVI values range from 0.21 to 0.24 and 0.38 to 0.40 accordingly [131].

3.6.5. Enhanced Vegetation Index and Visible Atmospheric Resistant Index

These two indices are alternatives to NDVI. The Enhanced Vegetation Index (EVI) considers atmospheric and canopy noise, while the sensitivity to high density vegetation is greater, according to the following equation [233]:

$$\text{EVI} = \text{G}\left[\frac{\text{NIR} - \text{R}}{\text{NIR} + \text{C}_1 \cdot \text{R} - \text{C}_2 \cdot \text{B} + \text{L}}\right] \tag{53}$$

where G, C1, and C2 are the gain factor coefficient (equal to 2.5) and the aerosol resistance terms (equal to 6 and 7.5, respectively); B stands for the blue band (with a wavelength range from 0.43 μm to 0.50 μm), while all others are as in previous equations.

The Visible Atmospheric Resistance Index (VARI) considers the atmospheric noise as well; however, it requires data from the visible spectrum, in line with the following relationship [133]:

$$\text{VARI} = \frac{\text{G} - \text{R}}{\text{G} + \text{R} - \text{B}} \tag{54}$$

3.6.5.1. Fire Potential Index Model and Modifications

Fire Potential Index (FPI), which combined satellite and field observations with high correlation to fire incidents. FPI was developed as an alternative to the complicate NFDRS calculations, while its intended accuracy approximates the 1 km [70]. FPI embodies some of the remote sensing indices mentioned in earlier sections as well as the fuel models proposed by the developers of NFDRS. The computational procedure of FPI alongside the two modifications is presented in paragraph S2.18 in Supplementary Material, Tables S41 and S42 [31,61,65,67,133,134]. Finally, the FPI has been proven to be reliable in environmentally diverted areas [133,134] although the ignition source of the fire incidents is ignored.

4. Discussion

The 63 systems indices reported in the current review incorporate environmental parameters for assessing directly or indirectly the fire danger in wildlands. However, there is a variety in parameters used as input for the analyzed systems, while their respective significance, impact, and calculation procedures also differ from case to case. Therefore, inputs, calculations, and outputs are the core parts of the evaluation process. Table 2 displays the relationships between systems and input parameters except for the remote sensing indices, as in these, the input parameters are the reflectance values of satellite images. For assessing the performance of the systems and indices in terms of inputs, calculations, and outputs, thirteen criteria were established according to the cited references of the current review, which were grouped in four categories: (1) computational procedure; (2) fire characteristics; (3) modularity; and (4) credibility. The final grade is the sum of all points derived from these criteria.

4.1. Computational Procedure

Five criteria are incorporated in the present group: (1) calculation complexity, defined by the number of equations and tables needed for the calculation of an index; (2) required data volume, defined by the number and the form of the data; (3) input data complexity, defined by the difficulty to acquire or measure the input data; (4) units which can be in SI or in US customary units; and (5) accumulated index related to previous calculations. The first three are rated on the scale 0–5, with 5 implying the less complex and 0 the most challenging to estimate. If the unit system differs from SI, then a point is subtracted from the sum of the first five criteria, while the same happens in the case that an index is cumulous, as different units and cumulus indices require additional calculations. The final result is divided by two in order to ensure equal weights to the following criteria.

4.2. Fire Characteristics

Two criteria are included in fire characteristics: (1) input variables type, defined by the first line of Table 2, and (2) fire danger aspect, related to fire ignition, spread, or severity. For every variable type and fire danger aspect, a point is added to the sum of the criteria for every index, as indices including more types of parameters and fire characteristics are considered as the most integrated.

Table 2. Systems and indices analyzed in terms of input parameters.

	Meteorology								Vegetation								Topography			Hydrology									
Index	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**	**U**	**V**	**W**	**X**	**Y**	**Z**	**a**	**b**	**c**	**Σ**
CFFDRS	X	X	X		X			X																						5
NFDRS	X	X	X		X		X			X																				6
Fosberg	X	X	X																											3
mFosberg	X	X	X		X																X									5
BEHAVE	X		X	X							X	X	X			X	X		X	X										10
CBI	X	X																												2
HDWI	X	X	X																											3
LASI	X					X												X												3
FFDI	X	X	X		X																X									3
GFDI	X	X	X									X	X																	3
FFBT	X	X	X			X			X		X																			5
SFDI	X	X	X																											3
LFDI	X	X	X		X																X									5
FMA		X																			X									2
FMA+		X	X																		X									3
IRM	X	X	X																		X									4
RF	X	X			X			X			X							X												6
EPI					X																			X						2
PEI					X																			X						2
r (Orieux)	X							X														X								3
I87	X	X	X					X	X													X								6
Numerical	X		X			X	X																							4
Ifa	X		X		X	X																								4
ICONA	X	X	X				X		X	X	X								X	X										9
CFS	X	X	X		X																X									5
IREPI																						X	X							2
IFI	X	X	X		X					X					X	X			X	X					X				X	11
DMRIF	X		X		X																X	X								5
Lourenco	X	X																												2
Lourenco$_{_m100}$	X	X	X																											3
Lourenco_f	X	X	X																											3
AI	X	X																												2
BIt					X																	X								2
I_{Br}	X				X																									2
TLI	X					X															X									3

Table 2. *Cont.*

	Meteorology									**Vegetation**								**Topography**			**Hydrology**									
Index	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**	**U**	**V**	**W**	**X**	**Y**	**Z**	**a**	**b**	**c**	**Σ**
NI	X					X															X									3
mNI	X					X															X									3
Zhdanko	X					X															X									3
M68	X	X																												2
mM68	X	X																												2
DW	X	X			X					X				X										X	X				X	8
MDI																					X									1
KBDI	X				X																					X	X	X		5
SDI	X				X											X						X				X	X	X		7
PDSI					X			X														X	X			X	X	X		6
RDI					X																	X								2
CWD																						X	X							2
VPD	X	X																												2
DI										X							X													2
Σ	38	27	22	1	20	8	3	5	3	5	4	2	2	1	1	3	2	2	3	3	13	9	3	3	2	3	3	3	2	

Legend (Column heading)

A	Temperature	K	Vegetation type	U	Drought period
B	Relative humidity	L	Curing degree	V	Potential Evapotranspiration
C	Wind speed	M	Fuel quantity	W	Actual Evapotranspiration
D	Wind direction	N	Leaf area index	X	Evaporation
E	Precipitation	O	Leaf area density	Y	Latent Heat of Evaporation
F	Dew point temperature	P	Canopy characteristics	Z	Interception
G	Clouds concentration	Q	Plants physiology	a	Runoff
H	Latitude	R	Elevation	b	Recharge
I	Date and/or Time	S	Slope	c	Solar Radiation
J	Fuel moisture	T	Aspect	Σ	Sum

4.3. Modularity

Two criteria are included as well in this group: (1) useful subcomponents related to intermediate outputs of the fire danger systems and (2) embodiment of other indices. Both are rated in a binary form, adding a point to the overall sum for every criterion that is fulfilled. Modularity is not a necessity; however, it can be considered as a leverage in the calculation process as well as in the integration of the deployed indices.

4.4. Credibility

The final category can be considered as the most essential in operating terms and consists of four criteria: (1) calculation basis, referring to the theoretical background concerning each system's development; (2) output categorization, concerning the clarity and the relevance of the output to the fire danger rating; (3) validation, concerning the estimation of the system index values in real scenarios and based on the selected studies of this review; and (4) adaptability, related to the degree that a system has been successfully tested in different environments. In the first one, six cases can be distinguished: arbitrary, empirical, scientific-based systems, and their combinations per two. Arbitrary systems are considered less credible, especially in different environments; thus, no points are added in the evaluation process. Empirical systems are developed to be more well-suited to local conditions; hence, these systems are rated with two points, while the mixture of arbitrary-empirical basis is rated with one point. Scientific-based systems provide enhanced credibility; therefore, the respective rate equals three, the mixture of scientific-arbitrary basis is rated with two, and lastly, the mixture of scientific-empirical basis is rated with four, as it is the most complete approach. In the second one, the output categorization can be clear and immediately related to fire danger, moderately clear and related to fire danger, and not clear or not immediately related to fire danger, with ratings being 1, 0, and –1, respectively. In the third and the fourth criteria, the validation results and adaptability are rated from 0 concerning systems that have not been yet deployed and from 3 concerning systems that have been used in almost every environment for a long period of time. The results of the evaluation procedure are displayed in Table 3. The results presented in Table 3 use the same weight for all criteria although the first and the last group are considered of higher importance as more criteria and points are included. Other combinations of weights can also be defined. NI, AI, KBD and NDVI are the top-performing indices, while IREPI, I_{Br}, CWD, and DI have the lowest scores.

Table 3. The evaluation of systems and indices for fire danger rating.

	S1					**Σ**	**S2**		**Σ**	**S3**		**Σ**	**S4**				**Σ**	**Grade**
Index	**A**	**B**	**C**	**D**	**E**		**F**	**G**		**H**	**I**		**J**	**K**	**L**	**M**		
CFFDRS	1	2	4	SI	−1	6	m	i	2	1	0	1	se	1	3	3	11	17
NFDRS	0	0	3	O	0	2	m,v,t	i,b,S	6	1	1	2	se	0	3	2	9	18
Fosberg	3	4	5	O	0	11	m	i	2	0	0	0	s	1	2	1	7	14.5
Fosberg +	2	3	5	O	0	9	m	i	2	0	1	1	s	1	1	1	6	13.5
BEHAVE	0	0	3	O	0	2	m,v,t	b,S	5	1	1	2	se	1	2	1	8	17
CBI	5	5	5	SI	0	15	m	i	2	0	0	0	e	1	1	1	5	14.5
HDWI	4	4	5	SI	0	13	m	i	2	0	0	0	s	−1	1	1	4	12.5
LASI	5	4	1	SI	0	10	m	i,S	3	0	0	0	a	1	3	2	6	14
FFDI	2	2	5	SI	−1	8	m	i	2	1	1	2	se	1	3	2	10	18
GFDI	4	3	4	SI	0	11	m,v	i	3	0	0	0	se	1	2	1	8	16.5
FFBT	1	2	3	SI	0	6	m,v	i	3	0	0	0	se	1	1	0	6	12
SFDI	5	5	5	SI	0	15	m	i	2	1	0	1	se	1	1	1	7	17.5
LFDI	4	4	4	SI	0	12	m,h	i	3	0	0	0	se	1	2	1	8	17
FMA	5	5	5	SI	−1	14	m	i	2	0	0	0	ea	1	2	1	5	14
FMA+	5	4	5	SI	−1	13	m	i	2	0	0	0	ea	1	2	1	5	13.5
IRM	5	4	5	SI	0	14	m	i	2	0	0	0	e	1	1	1	5	14
RF	3	2	3	SI	0	8	m,v	i	3	1	0	1	se	1	2	2	9	17

Table 3. *Cont.*

	S1					Σ	S2		Σ	S3		Σ	S4				Σ	Grade
Index	**A**	**B**	**C**	**D**	**E**		**F**	**G**		**H**	**I**		**J**	**K**	**L**	**M**		
EPI	5	5	5	SI	−1	14	m,h	i	3	0	0	0	a	−1	1	1	1	11
PEI	5	5	5	SI	−1	14	m,h	i	3	0	0	0	a	−1	1	1	1	11
r (Orieux)	2	3	4	SI	−1	8	m,h	i	3	1	0	1	ea	1	2	1	5	13
I87	2	3	4	SI	−1	8	m,h	i	3	0	1	1	sa	−1	2	1	4	12
Numerical	2	4	5	SI	−1	10	m	i	2	1	1	2	sa	1	1	1	5	14
Lourenco	5	5	5	SI	0	15	m	i	2	0	0	0	a	1	2	1	4	13.5
Lourenco$_{_m100}$	5	4	5	SI	0	14	m	i	2	0	0	0	a	1	2	1	4	13
Lourenco_f	5	5	4	SI	0	14	m	i	2	0	0	0	ea	1	2	1	5	14
Ifa	4	4	5	SI	−1	12	m	i	2	0	0	0	se	1	2	1	8	16
ICONA	3	1	3	SI	0	7	m,v,t	i	4	1	0	1	se	1	2	1	8	16.5
CFS	3	3	3	SI	−1	8	m,h	i	3	0	0	0	sa	1	2	1	6	13
IREPI	3	5	5	SI	0	13	h	i	2	0	0	0	a	−1	2	0	1	9.5
IFI	2	0	1	SI	0	3	m,v,h,t	i	5	1	0	1	sa	1	1	0	4	11.5
DMRIF	4	3	4	SI	−1	10	m,h	i	3	0	1	1	sa	1	2	1	6	15
AI	5	5	5	SI	0	15	m	i	2	0	0	0	sa	1	3	3	9	18.5
BIt	4	4	5	SI	−1	12	m,h	i	3	0	0	0	ea	1	1	1	4	13
I_{Br}	5	5	4	SI	−1	13	m	i	2	0	0	0	a	−1	1	1	1	9.5
TLI	5	4	5	SI	−1	13	m	i	2	0	0	0	sa	1	2	2	7	15.5
NI	5	5	4	SI	−1	13	m,h	i	3	0	0	0	s	1	3	3	10	19.5
mNI	4	4	4	SI	−1	11	m,h	i	3	0	0	0	se	1	1	1	7	15.5
Zhdanko	4	4	4	SI	−1	11	m,h	i	3	0	0	0	se	1	1	1	7	15.5
M68	3	4	4	SI	−1	10	m,h	i	3	0	0	0	se	1	1	1	7	15
mM68	3	4	4	SI	−1	10	m,h	i	3	0	0	0	se	1	2	1	8	16
DW	2	0	0	SI	0	2	m,h	i	3	0	0	0	se	1	2	1	8	12
MDI	5	5	5	SI	−1	14	h	i	2	0	0	0	s	−1	1	1	4	13
KBDI	4	3	4	O	−1	9	m,h	i	3	0	0	0	se	1	3	3	11	18.5
SDI	3	3	3	SI	−1	8	m,h	i	3	0	0	0	se	1	3	2	10	17
PDSI	1	2	1	O	−1	2	m,h	i	3	0	0	0	se	0	3	2	9	13
RDI	5	5	4	SI	−1	13	m,h	i	3	0	0	0	s	0	1	0	4	13.5
CWD	4	3	3	SI	0	10	h	i	2	0	0	0	a	−1	2	1	2	9
VPD	5	5	5	SI	0	15	m	i	2	0	0	0	e	−1	2	2	5	14.5
DI	3	1	1	SI	0	5	h	i,S	3	0	0	0	s	−1	0	0	2	7.5
NDVI	5	5	5	SI	0	15	v	i,S	3	0	0	0	s	−1	3	3	8	18.5
RG	5	5	4	SI	−1	13	v	i,S	3	0	1	1	se	−1	2	2	7	17.5
VG	5	5	4	SI	−1	13	v	i,S	3	0	1	1	se	−1	1	1	5	15.5
NDWI	5	5	5	SI	0	15	v	i,S	3	0	0	0	s	−1	1	1	4	14.5
NDWIm	5	5	5	SI	0	15	v	i,S	3	0	0	0	s	−1	0	1	3	13.5
NDII6	5	5	5	SI	0	15	v	i,S	3	0	0	0	s	−1	0	1	3	13.5
NDII7	5	5	5	SI	0	15	v	i,S	3	0	0	0	s	−1	0	1	3	13.5
NMDI	5	5	5	SI	0	15	v	i,S	3	0	0	0	s	−1	0	1	3	13.5
SAVI	5	5	5	SI	0	15	v	i,S	3	0	0	0	s	−1	0	1	3	13.5
EVI	5	5	5	SI	0	15	v	i,S	3	0	0	0	s	−1	0	1	3	13.5
VARI	5	5	5	SI	0	15	v	i,S	3	0	0	0	s	−1	0	1	3	13.5
FPI	2	3	4	SI	−1	8	m,v	i,S	4	0	1	1	se	−1	2	2	7	16
FPI_m1	3	3	4	SI	−1	9	m,v	i,S	4	0	1	1	se	−1	1	1	5	14.5
FPI_m2	3	3	4	SI	−1	9	m,v	i,S	4	0	1	1	se	−1	1	1	5	14.5

Legend (Column heading)							
S1	Computational procedure	D	Units	L	Validation	B	Behavior
S2	Fire characteristics	E	Accumulated index	M	Adaptability	S	Severity
S3	Modularity	F	Fire danger variables	N	Accuracy	A	Arbitrary
S4	Credibility	G	Fire danger aspect	M	Meteorology	E	Empirical

Table 3. *Cont.*

	S1					**Σ**	**S2**		**Σ**	**S3**		**Σ**	**S4**				**Σ**	**Grade**
Index	**A**	**B**	**C**	**D**	**E**		**F**	**G**		**H**	**I**		**J**	**K**	**L**	**M**		

Σ	Sum	H	Useful subcomponents	V	Vegetation	S	Scientific
A	Calculation complexity	I	Embodiment of other indices	T	Topography	Si	International system
B	Required data volume	J	Development basis	H	Hydrology	O	Other
C	Input data complexity	K	Output interpretation	I	Ignition		

4.5. Accuracy

The last but also the most important step for selecting the best fire danger rating system or index is estimating the respective accuracy. For the evaluation process, four regions within the Greek territory were selected, as depicted in Figure 2: (1) Mt. Penteli region in Attica; (2) the Regional Authority of Evros, northeastern Greece; (3) the Region of Kimi-Aliveri in Evoia; and (4) the Regional Authority of Helia-Achaia. As shown in Figure 2, fire incidents for the period 01/06/2022–31/07/2022 were gathered from satellite images provided by the NASA-FIRMS (https://firms.modaps.eosdis.nasa.gov/map/, accessed on 1 August 2022) [234] as well as meteorological data from the local weather stations, provided by the National Weather Service of Greece and the National Observatory of Athens.

Figure 2. Fire incidents and weather stations in the areas of interest.

For calculating the values of the indices for every region, a computer program in Python was developed according to the equations presented in this article and the respective SM file. The program uses as input the meteorological data, i.e., temperature, relative humidity, wind speed, and precipitation depth, while it calculates other intermediate parameters needed for the computation of the fire indices, such as the number of days of drought, evapotranspiration, etc. The computational procedure concludes with the output values of every index on daily basis from 1 June 2022 to 31 July 2022. Unfortunately, due to lack of some specialized data, not all presented indices were used. The following indices were excluded from this accuracy experiment: BEHAVE, LASI, FFBT, ICONA, IREPI, PDSI, CWD, Darcy, as well as remote sensing indices, as a different approach would have to be adopted; thus, the comparison would be unrepresentative.

According to the index values in relation to fire incident or no fire occurrence, the following four cases were examined: (1a) no fire occurrence and index "hit"; (1b) no fire occurrence and index "miss"; (2a) fire occurrence and index "hit"; and (2b) fire occurrence and index "miss". In case of no fire incident, an index hit is considered as the outcome value out of the range of extreme fire danger class—according to SM tables. Accordingly, in case of a fire event, an index hit is when the respective outcome value is in the range of the extreme fire danger class. Fire danger classes for some of the indices had to be redefined to be realistic in the Greek environment in order to fit with the outcome value ranges. Cases 1a and 1b were marked with 1 and 0 points, respectively, per day of calculations, while cases 2a and 2b, which were considered more important for fire management, were marked with 2 and −2, respectively. For the final score, all index marks were normalized by dividing with 277 (the maximum mark for all days and all regions). The five most-accurate indices for the tested period and regions in Greece were proven to be the following: (1) NI; (2) KBDI; (3) SFDI; (4) FFDI5; and (5) SDI. The five least-accurate indices were as follows: (1) DW; (2) r (Orieux); (3) IBr; (4) IFI; and (5) PEI. The NI has also been successfully applied in mountainous areas in Greece [235–237], corroborating the findings of the present article.

Eventually, the scores of indices (presented in Table 3) and the accuracy marks were summed, using equal weights (divided with the respective maximum grade), to produce the final evaluation of the included indices, as shown in Table 4.

Table 4. Overall performance of environmental fire danger systems and indices based on the five groups of criteria.

Index	Score	Index	Score	Index	Score
NI	0.68	Zhdanko	0.56	pmM68	0.51
KBDI	0.65	M68	0.55	HDWI	0.49
SFDI	0.64	CBI	0.55	FMA	0.49
FFDI5	0.62	RF	0.55	RDI	0.49
SDI	0.61	DMRIF	0.54	CFS	0.48
LFDI	0.60	IRM	0.54	EPI	0.47
GFDI5	0.59	Fosberg	0.53	Numerical	0.46
TLI	0.59	MDI	0.53	FMA+	0.46
CFFDRS	0.59	Lourenco_f	0.53	I87	0.44
Ifa	0.59	Lourenco	0.53	DW	0.44
AI	0.58	BIt	0.52	r (Orieux)	0.43
NFDRS	0.58	$\text{Lourenco}_{\text{\_m100}}$	0.52	I_{Br}	0.43
mNI	0.57	Fosberg+	0.51	IFI	0.42
VPD	0.57	mM68	0.51	PEI	0.41

5. Conclusions

A total of 63 environmental fire danger rating systems from across the globe were analyzed and compared. The most important parameters were associated with weather and hydrology although the most accurate indices required only two to five inputs. Some of the most-used systems—also reported in the present review—require complex calculations. However, the top-rated indices and the most accurate as well were those with simpler formulas and procedures. In addition, indices developed in a specific region have been proven to be more accurate in different environments—as most of the Mediterranean indices included in the current study underperformed in Greece. Additionally, the most complete systems—such as the CFFDRS and the NFDRS—had a fine performance, while the FFDI5 reached near the top, leading to the conclusion that if these systems adapt better to the local conditions, their performance will be greater than the respective one of the simpler indices. Finally, this review corroborated the inadequacy of the existing environmental fire danger rating systems in predicting modern day incidents, as the top-performing systems had an accuracy of 60–66% and a total score of 59–68%, indicating the need for an integrated approach including social and other factors.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12010194/s1, Paragraphs S2.1–S2.18; Tables S1–S42. The SM file presents the calculation procedure and value range for each system and index. Also, the SM includes the nomenclature.

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Data Availability Statement: Meteorological open data were downloaded from the National Observatory of Athens, https://www.meteo.gr/Gmap.cfm (accessed on 1 September 2022). Fire incidents data were downloaded from the National Fire Service of Greece, https://www.fireservice.gr/en_US/stoicheia-symbanton (accessed on 1 September 2022). Spatial open data were downloaded from https://geodata.gov.gr/en/ (accessed on 1 September 2022). For meteorological data processing, the Python open-source programming language was used, and for spatial analysis and mapping, the open-source Quantum GIS was deployed. All data are included in the paper.

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