

Review

Wildfire Likelihood's Elements: A Literature Review

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Abstract: Wildfires occur in different climatic zones, forest cover types and eras. Wildfire or forest fire has always shaped the landscape. Different methodologies and indexes have emerged to determine the likelihood of wildfire, commonly confused with the wildfire hazard. However, none of these are universal or portable. In this paper, we have gone through several articles, projects and books. The aim was to identify factors related to the ignition of a wildfire. Consequently, 28 factors were presented and categorized into climatic, topographic, *in-situ*, historical and anthropogenic factors. It is the first step in building a generalized, acceptable and portable method to determine the wildfire risk. Its creation is strongly related to the prevention and better assessment of this phenomenon.

Keywords: wildfire; likelihood; hazard; ignition factors; fire occurrence

1. Introduction

The first thought that might cross our minds when talking about a wildfire is the image of destruction, pain and suffering. While some authors [1–4] and local dwellers classify its occurrence as a disaster, wildfire is a natural phenomenon. By definition, *wildfire* is generally the fire that spreads over a minimum area of one hectare [5], where one or more types of vegetation are concerned. Actually, several terms were used across the globe to describe vegetation fires in areas outside the urban environment [6].

In the United States, *wildland fire* defines “any non-structure fire that occurs in the wildland and includes wildfire, wildland fire use, and prescribed fire” [7]. In Australia, the term *bushfire* is being used to describe any vegetation fire [8], whereas, the generic term *wildfire* describes “any unplanned vegetation fire, including grass fires, forest fires and scrub fires” [8]. The term *forest fire* is currently used by the European Commission Joint Research Centre Institute for Environment and Sustainability [9], already found in their annual report on fires in European countries. In Canada, *forest fire* and *wildfire* are defined by the Canadian Interagency Forest Fire Center [10]. According to them, *forest fire* is “any wildfire or prescribed fire that is burning in forested areas, grass, or alpine/tundra vegetation”, while *wildfire* means “an unplanned or unwanted natural or human-caused fire, as contrasted with a prescribed fire.” In this review, we considered and discussed all these described fires except for the prescribed fire.

Wildfires occur worldwide, but in the United States alone there are an estimated 60,000–80,000 wildfires per year according to the National Interagency Fire Center (NIFC) in 2015. Actually, worldwide forest areas are presenting a fluctuating trend over the years. Before the Industrial Revolution (1760–1840), almost half of the terrestrial surfaces were covered with forests (*i.e.*, 5.9 billion hectares). This area was diminished by half then by a fifth in 1955 and 1980, respectively. In 2000, while a further decline was expected, it was found that forest areas increased from 2.5 to 4.08 billion hectares. It was mainly the consequence of major reforestation efforts. Anyhow, in 2010, these areas decreased by 50 million hectares [11]. Accordingly, the transition from primary forests to forest stands has been made.

Wildfire might be beneficial. By reducing fuel loads, it minimizes the intensity of each fire that occurs in subsequent years, consequently decreasing the impact of fire on fire-tolerant plants and burrowing animals. Furthermore, wildfire allows more open spaces for new and different kinds of vegetation to grow and receive sunlight, promoting the sustainable development of the forest. An increase of species resiliency might perhaps be achieved by eliminating insects and diseases [12]. Moreover, some vegetative species, especially mushrooms (*e.g.*, *Geopyxis carbonaria*, *Ascobolus carbonarius* *Peziza petersii*, *Pyronema confluens*), benefit from forest fires, since they grow on burnt trunks [13]. Even though the wildfire is a natural phenomenon, it has many undesirable impacts on human safety and health, regional economies as well as climate change. In addition, the secondary effects of wildfires, including erosion, landslides, introduction of invasive species, and changes in water quality, are often more disastrous than the fire itself [14,15].

Currently, several countries are researching fire management systems, such as Canada, South America, Mexico, and South Africa [16]. On a global scale, different systems are present to map and forecast near real time event information (*e.g.*, Global Fire Monitoring Center (GFMC), Experimental Climate Prediction Center (ECPC), Global Fire Information Management System (GFIMS), Global Early Warning System for Wildland Fires, *etc.*). Their purpose is to reduce the wildfire risk. In fact, wildfire risk is divided into two components: Likelihood, which is the probability of ignition or burning, and hazard, including intensity and effects—which can be positive or negative [17–19]. This definition did not emerge until 2005, where a conference was held in Portland, USA, which highlighted the substantial interest in the wildfire science community to standardize and operationalize definitions such as risk, hazard, and fire danger. Despite those efforts, these terms are interchanging constantly. By definition, hazard describes the potential for loss given a fire event; however, it does not refer to the likelihood of the event occurring. Fire danger illustrates the short-term outlook for fire occurrence while using short-term weather forecasts [19].

In many parts of the world, local communities are often blamed for what are considered harmful forest fires. Because dwellers usually have most at stake in an extreme event—such as a wildfire—they should clearly be involved in mitigating these unwanted events. Fire and forest management institutions should perceive local communities as part of the solution, and certainly not part of the problem. At the end, the best way to stop a wildfire is to make sure it never starts.

While developed countries spend billions each year in order to reduce the impact of forest fires, the creation of a wildfire likelihood map may be a critical tool to predict, prevent and better assess the areas with the highest exposure to wildfire. It shall contribute to the development of sustainable forest management plans. Similarly, this map shall provide an attractive image to motivate the general public to join forces with decision-makers. For the reasons outlined above, an identification of the causes behind the ignition of the wildfire is crucial to protect and save the international natural forest heritage.

The wildfire likelihood, commonly confused with the wildfire hazard, has been determined via different type of factors and methodologies. In this report, we discussed the diverse approaches used in the literature worldwide. Then, we pinpointed each factor found throughout the collected references. It is important to note that only the ignition factors, defining the probability of ignition or burning, are required—not the initial and the free propagation factors which are defined as the second and third phases in a wildfire, respectively.

2. The Methodologies behind the Wildfire Likelihood

A first attempt to identify ignition factors was developed by the US and Canadian forest services nearly 50 years ago; this saw the establishment of the “physical evidence” method [20]. However, this approach was tested initially in 1989, by Sérgio Correia in Portugal [20]. As a result, seven investigation brigades were formed in 1990 in the northern and central parts of Portugal, and in 1991 in Spain [21]. This method involves an analysis of the boundary’s geometry of the burnt area and an examination of physical evidence on stones, vegetation, tree trunks, posts, fences, *etc.* [22,23], to establish the direction movement behavior of fire, which leads to the determination of the causes for its occurrence. It examined carefully the place where the fire ignites to exhaust all possibilities of finding one or more material clues that could be identified as the heat source. This method does not allow the determination of the cause of all fires [20], though. Anyhow, France and Italy joined the initiative of creating a wildfire likelihood map in 1997 and 2000, respectively [20]. The Prefect is leading the research in France, and Corpo Forestale in Italy [24].

Classifications of the driving forces of wildfires into several categories are presented in numerous studies (e.g., [25–28]). These categories could be as follows: climatic factors (including temperature, humidity, wind), topographic factors (including slope and aspect), vegetation factors (including drought state, vegetation type), and finally, human factors (including road network, Wildfire–Urban Interface (WUI)). However, Dauriac *et al.* [27] extended the vegetation factors by adding vegetation moisture: He used the Mid Infrared (MIR) spectrum (1300–1800 nm) to calculate the Foliar Moisture Content (FMC). Later, weighting factors were introduced. Setiawan [29], for instance, evaluates the forest fire risk in peatlands in Malaysia. In his research, factors affecting the ignition of a forest fire were weighted with an analytic hierarchy process (AHP). Most studies one may encounter are found to follow this type of methodology.

Another study conducted by the forest fighter team of Cemagref Institute in Aix-en-Provence, France has developed a spatial assessment method for the forest fire likelihood across the Maures Moutains [30]. They have proposed to classify the driving forces into three categories (*i.e.*, those that affect the ignition of the wildfire, its initial spread and its free propagation). The first set of likelihood categories includes the presence or absence of human activities and the presence or absence of fuel. The second set of likelihood categories consists of the wind direction. The third set of likelihood categories is mainly related to wind speed. It also defines an index reflecting the angle of incidence of the wind on the earth's surface.

Gonzalez *et al.* [31] provided new insight in establishing the wildfire likelihood. They used the probabilities of occurrence of forest fire. In his study, driving factors were divided on one hand into controllable and uncontrollable variables, and on the other hand, into known and unknown variables' values. An example of variables that are both controllable and known are the density and species composition of the vegetative population, as well as the vertical structure of the canopy. The prediction of the exact weather conditions in a forest is often inaccurate (uncontrollable and unknown). Long-term averages of climatic factors are known (uncontrollable and known). In addition, new variables were considered in this study—*i.e.*, basal area, tree diameter at breast height (DBH), and the hardwood proportion of the total surface. According to his findings, the probability of a forest to be affected by a fire increases with low altitude, higher DBH, smaller basal diameter, denser hardwood fraction, higher proportion of conifers and an increase in the variation of trees' diameter.

Jappiot *et al.* [32] introduced a top-down approach that was described as “based on the needs.” The authors distinguished between three types of representation of each element of likelihood categories: The probabilistic mode, which is based solely on statistical data to represent an element of likelihood; The semi-probabilistic method, which mainly uses historical data to adjust non-historical components, but also includes the expertise and experimentations; Deterministic mode, which requires a good knowledge of the mechanisms related to fire's outbreak and spreading.

Furthermore, several authors (*e.g.*, [33–36]) linked the outbreak of forest fires to the arrangement of local houses and existing vegetation. As a result, numerous studies [37,38] discussed the effect of the Wildland–Urban Interface (WUI) on the wildfire likelihood determination. The result was an establishment of 12 kinds of typologies concerning the Wildland–Urban Interface, diverse vegetation and urban densities. Among these types, the isolated Wildland–Urban Interface, which is characterized by a low-density housing, represents the highest level of fire risk.

In 2009, Ganteaume *et al.* [39] chose to investigate the ground fuel flammability and its ability to cause a fire. They concluded that at higher density and moisture content of the carburant, an increase of the time until ignition of a fire is observed.

Most recently, some researchers have used a “back trajectory analysis” or have studied the “wildfire synoptic climatology”, in order to provide ensemble weather factors to be included in a forest fire likelihood identification [40].

Studies relating land-cover types to wildfire have been conducted as well. Results show that for most land-cover classes, fire behaves selectively. In Europe, for instance, shrublands and grasslands were the most preferred by fire, whereas, artificial surfaces and agricultural areas were less fire prone [41]. It was also the case in Portugal [42,43]. In Italy, the number of fire occurrences was higher than expected in

urban and agricultural areas, while in grasslands and shrublands, mean fire size was significantly larger than expected [44].

Other authors adapted universal indexes such as the Fire Weather Index (FWI) (e.g., [45–47]), the Fire Potential Index (FPI) (e.g., [48–50]), the McArthur Forest Fire Danger Index (FFDI) (e.g., [51,52]), the Forest Fire Risk Index (ICRIF) (e.g., [53]), and the Keetch-Byram Drought Index (KBDI) (e.g., [54–56]). The most documented index is the Canadian Forest Fire Weather Index (FWI). It integrates the temperature, the relative humidity, the wind, and the rain. This index is an important part of the Canadian Forest Fire Danger Rating System (CFFDRS). Flannigan *et al.* [57] for instance, used a model based on the FWI to study fire in Canada since 1850.

Table 1. Preliminary classification of different factors deduced from literature.

Preliminary Classification	Factors
A. Climatic Factors	Precipitation ¹
	Temperature ¹
	Air humidity ¹
	Wind speed ¹
	Wind direction ¹
	Current drought ¹
	Long-term drought ¹
	Evapotranspiration ¹
	Illumination time ¹
	Illumination intensity ¹
B. Topographic Factors	Slope ¹
	Aspect ¹
	Altitude ¹
C. In-situ Factors	Fuel type ²
	Fuel density ¹
	Soil moisture ¹
	Soil texture ²
	Soil organic matter ¹
	Trees age ¹
	Basal area ¹
	Hardwood proportion ¹
	Tree diameter at breast height ¹
D. Historical Factor	Disease/illness index ²
	Probability of occurrence of a wildfire ¹
E. Anthropogenic Factors	Proximity to agricultural land ¹
	Proximity to roads ¹
	Proximity to urban areas (Wildland-Urban Interface) ¹
	Proximity to recreation areas, breeding grounds, exploitation zones, etc. ¹

¹ quantitative variable; ² qualitative variable.

While a huge amount of researchers discussed wildfire ignition, what we noticed, after consulting over 100 manuscripts worldwide, is that there is a lack of generalization of the driving forces behind the occurrence of wildfires. Several authors had this same thought (e.g., [58–61]). Hence, we collected every

factor found in the literature. Consequently, 28 factors were identified and classified into five different categories (*i.e.*, climatic, topographic, *in-situ*, historical and anthropogenic factors) and were presented in Table 1. These classifications were based on the logical distribution of factors. In fact, climatic factors include climate-related driving forces such as precipitation, temperature, humidity, *etc.* Topographic factors encompass elements related directly to topography (*i.e.*, altitude, slope and aspect). *In-situ* factors are those that need ground measurements. They correspond to fuel type and density, soil moisture and texture, trees age, hardwood proportion, *etc.* Historical factors are the historical/archived databases (*i.e.*, number or probability of occurrence of a wildfire). Anthropogenic factors encompass the proximity to human-disturbance areas. They define the constant human interference regions without considering intentional wildfires and arsons.

The exhaustive and systemic identification of ignition-related factors is important in terms of defining a standard set of elements used worldwide that any wildfire study should begin with. Due to the lack of data in some regions, for some classifications, some of the missing factors had to be substituted with others that could be related to them. Ultimately, when factors for a study area were defined, models or indexes could be generated: This should facilitate the monitoring of this phenomenon as well as the building of an early warning system.

According to the fire triangle, any fire needs three inevitable components (*i.e.*, fuel, oxygen and heat) to be initiated. In wildfire, fuel is generally a form of vegetation. High water content creates an adverse effect. Then, higher precipitation and humidity (*i.e.*, air humidity or soil moisture) decrease the likelihood of a wildfire. In contrast, greater temperature diminishes water content, increasing the likelihood of forest fires. Wind speed and direction affect fire ignition by altering the quantity of oxygen—a primary component in the fire triangle—existing at a predefined location. These factors are included almost in any study related to wildfire. Drought and long term drought could also affect wildfire. In fact, in hot and dry conditions, early and extended fire seasons are noticed. It is what studies such as those by Flannigan *et al.* [57], Swetnam *et al.* [62], Skinner *et al.* [63], Bachelet *et al.* [64], showed by successfully correlating long-term weather anomalies and forest fires. Evapotranspiration is closely related to the remaining water content in the vegetation cover. It is actually a combination of evaporation and transpiration. Higher evapotranspiration increases the likelihood of a wildfire. Steeper slope means that a fire burns not only at high speed, but more vigorously. In addition, heat transfers by convection are encouraged. More importantly, slope can change the soil infiltration properties by reducing the amount of interception material that protects the soil against the impact of rain drops and slow runoff [65–68]. Different aspects result in different vegetation covers, temperatures, and illumination time. The likelihood of a wildfire could be affected in relation to the extent of different aspects. South and southwest aspects are the regions with the highest probability of wildfire occurrence [69,70]. As elevation increases, both precipitation and humidity increases while temperature decreases, and the vegetation cover becomes sparse. The likelihood of a wildfire is low. Fuels constitute the organic matter needed for the ignition of a fire. They represent one of the factors that are included in forest fires' assessment and a factor that humans can control [71,72]. The reduction of the fuel density and depth, particularly to less than 8 cm deep, allows a decrease in the probability of wildfire [70]. Furthermore, several authors (e.g., [31,73]) noted that the fuel type, quantity and distribution affect the frequency of fires. Trees age, basal area, hardwood proportion, and tree diameter at breast height were included in numerous studies (e.g., [31,73]). Disease/illness index (e.g., [64,74]),

soil texture (e.g., [68,74,75]), the probability of occurrence (e.g., [29,59,76,77]), illumination time and intensity (e.g., [57,74,78,79]) are all parameters found throughout the literature that assist in investigating the likelihood of a wildfire. In addition, according to the UNFAO, the apparent increase in catastrophic forest fires worldwide [80] is related to human interference [81]. In Europe, for instance, with its high population density, over 95% of fires are caused by human activities [82]. The presence of certain infrastructure such as roads, power lines, waste deposits, and railroads significantly increases the apparition of wildfire [27]. Increases in agricultural, industrial and recreation areas, *etc.* are also increasing the likelihood of wildfire. On the other hand, the Wildland–Urban Interface (WUI) has received increasing attention since the 1980s [83] and has been featured in several studies related to wildfires (e.g., [84–87]).

3. Conclusions

Wildfire is a natural phenomenon. Its numerous and complex consequences threaten human welfare and wellbeing. A determination of the likelihood of wildfire generates various positive outcomes, particularly in terms of prediction, prevention and better assessment of the affected areas.

While several methodologies and variables have been used to determine the likelihood of wildfire, each research study has developed its own approach. Defining factors that are related to the ignition of a wildfire is the first step to establishing an easy-to-apply and portable methodology. We have identified 28 factors that can be divided into climatic, topographic, *in-situ*, historical and anthropogenic factors. Of course, each driving factor has different influence according to the season and the environmental and socioeconomic context, including legislation and human behavior. The next step is to prove their statistical significance in each selected region. A universal model should be created in each climatic zone, followed by the use of weighting factors. The statistical methods/tests recommended to build these models are as follows: Adjusted R-Squared, Akaike's Information Criterion, Jarque-Bera *p*-value, Koenker (BP) Statistic *p*-value, Max Variance Inflation Factor, and Global Moran's I *p*-value. The use of remote sensing techniques in such studies plays a vital role. They provide reliable datasets for some of the proposed variables with high spatial, spectral and temporal precision.

Author Contributions

Jocelyne Adjizian-Gerard and Ghaleb Faour had the original idea for the study, and together with the lead author, Mario Mhawej, supervised the research work and was responsible for revising the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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