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A brief review of the effect of wildfires on rockfall occurrence

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Abstract. Wildfires and rockfalls are among the major hazards in forested mountainous regions across Europe. Understanding processes and conditions that lead to rockfalls during and after a wildfire in different geological contexts is, therefore, of great relevance. The increase of rockfalls associated with the occurrence of wildfires is connected to several factors, not only in the detached area but also in the propagation and affected area. Wildfires cause changes in the mechanical properties of rocks and discontinuities as well as the loss of protective capacity from vegetation, complemented by the effect induced by firefighting activities and by extreme temperatures that may deteriorate the installed protective measures. After the occurrence of a wildfire, there is an increase in the frequency and intensity of rockfalls in the burned area, causing a major impact of rockfalls on road networks and inhabited areas. Additionally, the rockfall risk perception is usually increased due to the removal of vegetation by wildfires, exposing both rock blocks and the rock mass. In this review, the main factors that influence the occurrence of rockfalls after a wildfire are briefly reviewed.

1. Introduction

Wildfires are very frequent in semi-arid and arid climates, particularly during the summer season where the high temperatures, the strong winds, and the scarcity of precipitation converge. During fires, the temperature can reach near 400 °C, causing important physical and chemical effects on the soil and rock mass [1]. According to the 'Annual Report on Forest Fires in Europe, Middle East and North Africa 2019' [2], Spain, Portugal and Poland are the European countries with the highest number of wildfires. In the last fifty years, almost 600,000 wildfires were recorded in Spain, affecting about 7.5 Mha, being the 1990s the decade with the highest number, with an average of 19,000 fires per year, and an average of 160,000 ha burnt per year [3]. During the last years, the number of fires and the burned area has decreased. Nevertheless, the occurrence of large wildfires (affected area > 500 ha) remains high. Wildfire activity is changing dangerously, as climatic conditions due to global warming clearly influence the frequency, severity, and extent of wildfires.

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In addition to the environmental effects, wildfires increase the frequency of landslides, and specifically debris flows [4–6] and rockfalls [7]. These post-fire processes increase the risk posed to infrastructures and people within the burned area. Several studies during the past decade analysed the susceptibility to debris flows in burned watersheds [8–12]. After a wildfire, there is an alteration of the hydrological and soil conditions by changing the evapo-transpiration and infiltration rates, which increase the probability of occurrence of debris flow [13]. These rapid slope-movements can be very dangerous, capable of causing significant damage and fatalities in a single event [10, 14].

In the case of rockfalls, a lack of exhaustive research on the effects of wildfires has been observed. Rockfalls are dangerous phenomena, due to high kinetic energy related to the velocity of the falling blocks. This often explains the difficulty of taking fast-enough and effective actions as well as of designing appropriate protection and mitigation measures [15, 16].

After detachment, boulders move by falling, bouncing, rolling, or sliding. A single block may be fragmented into several boulders during its impact with ground or trees. When the block loses enough kinetic energy, it stops, reaching its final stable position [17]. Understanding the conditions leading to rockfalls during and after a wildfire in differents geological contexts [16] is crucial, as rockfalls are very frequent in mountain ranges, coastal cliffs and slope cuts.

There are some studies in the literature that report the increase in rockfall-activity during and after wildfires [7, 17, 18]. This occurs by the confluence of rock fragmentation by high temperatures, changes in the rock mechanical conditions, and loss in the protective capacity of vegetation. In granular soils, chemical-mineralogical variations take place: dehydration, dihydroxylation or oxidation; while in rocks, mechanical effects by thermal expansion occur [19]. Furthermore, fires increase the erosional processes in the slope, modifying the original topography [20–22] which can significantly change the rockfall trajectories [20, 23].

Wildfires cause great social impacts such as home loss, property damage, number of residents evacuated and severe ecological effects. When wildfires occur in mountainous areas, the loss of vegetation exposes the rock and the perception of rockfall risk increases. This is the main reason behind the understanding of rockfall hazard impact from two perspectives: physical and social, focusing on civil works and built-up areas, but also on people's lives and their environment.

The review of effects of wildfire on rockfall occurrence is organized following schema showed in Figure 1. It is mainly divided into three zones: the *detached* or *source area* where rockfalls originate, the *detached area*, that is the portion of the talus where the rockfall mostly travels down the slope, and the *potential affection zone* where the majority of the boulders and fragments stops.

Regarding the *detached* or *source area*, we present the effects on the rock mass that are directly related with rockfall initiation processes due to thermal degradation of rock, crack initiation and damage stresses. Then, the study is focused on the *propagation zone* that is also modified when there is a loss of vegetation by the fire. Vegetation is extremely important to protect against rockfall, reducing the velocity and the rebound heights of falling rocks, therefore, it is necessary to consider its loss in the evaluation of the boulders trajectories, mainly the variation of restitution and friction coefficients in the numerical simulations. Finally, we present how influence wildfires in the degree of affection by rockfall, analysing their social and economic impact.

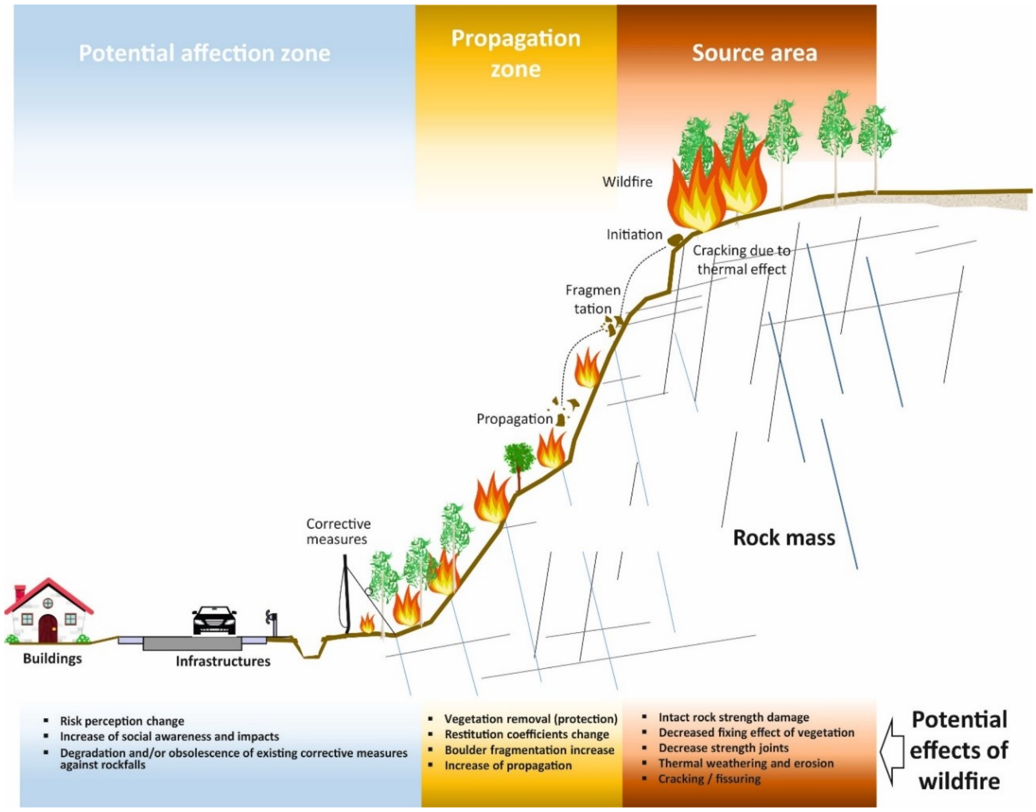

Figure 1. Diagram showing the main effects of wildfires on rockfall occurrence and the three main areas.

2. Effects of wildfires on the rock mass: *source area*

High temperatures induced by wildfires can relevantly affect the rock matrix. The thermal expansion of constituent minerals origins an increase of contact surfaces between them causing structural changes that affect the rock strength [24–26]. Processes such as dehydration or decarbonization can lead to relevant changes in the mechanical properties of rocks [25, 26]. Minero-chemical changes also cause polymorphic transformations, melting, and even the disappearance of certain minerals [27–29]. These processes are behind the development of new microcracks and the coalescence and enlargement of existing ones that are responsible for the important changes in the physical and mechanical properties of rocks after a fire. The strength loss, especially in compression, was studied in detail for granitoids and sandstones, observing decreases of up to 80% of UCS observed for temperatures about 800 to 1000 °C.

The effect of temperature on intact rocks has been widely studied in laboratory [30–33]. These studies allow evaluating the changes in the chemical, physical and mechanical properties of rocks when heated. Most of the studies use regular specimens of intact rock heated in an oven following standard heating curves, which represent the phenomena under study. These heating curves usually present three main stages: an initial heating ramp, between 1 to 15 ºC/min, starting at room temperature and reaching typical values of 200 to 1000 °C (this part of the curve represents the initiation of the fire); a second stage with constant temperature during an interval of time that varies from 1 to 24 h (this part of the curve represents the duration of the fire); a last stage, the cooling process, replicated in different ways: sometimes by cooling down the samples within the oven up to room temperature to simulate the slow and natural cooling of the rock, and sometimes in a faster way, by submerging the samples into water or even applying

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liquid-nitrogen to cause a thermal shock that reproduces the extinguishing operations.

The effect of the cooling method is also a factor of importance in rock masses affected by wildfires. Previous studies highlighted that the reduction of strength and elastic parameters of rocks is more relevant in rapidly cooled samples than in air-cooled (slowly cooled) samples, being the crack density increased due to sudden thermal shock [34–36].

The effect of temperature on the shear strength of joints has been scarcely studied. Some studies were focused on the evaluation of the shear strength of rock discontinuities that were subjected to thermal treatments at different temperatures (up to 800°C) by means of direct shear tests [37–39]. These results show a gradual decline of the peak shear strength as the temperature increases under normal loading condition. However, this thermal effect gradually became more reduced as the normal stress increased.

Wildfires mainly affect rock masses expanding the outer parts causing internal stresses that exceed tensile strength of the rock-forming fractures. The presence of matrix in detritic rocks causes a dampening effect of mineral crystal dilations. However, in massive rocks, the absence of matrix and the greater packing of the crystals increase the efforts between them as they dilate and cracking occurs. Considering massive rocks with similar porosity and mineral packing, those of carbonate composition have been found to be less sensitive to the action of fire than those of siliceous composition [19].

3. Changes in the slope: *propagation zone*

The occurrence of forest fires will remove the vegetation coverage and modify the soil and rock properties, affecting relevant factors or input parameters into numerical models for rock slope stability assessment, before and after the fire.

3.1. Vegetation loss

Vegetation (in general terms, trees and undergrowth) acts as a natural barrier for protection against rockfalls since they can significantly reduce the runout of rockfalls [40] and provides stability [18]. Vegetation not only decrease the intensity of rockfalls, reducing the energy and the velocity of the falling boulders, but also reduce the frequency of rockfall events [41, 42]. The distribution and types of trees on the slope influence this protective effect. An increase of the Diameter at Breast Height (DBH) has been reported to improve the capacity of block retention [43, 44]. Moreover, the role of roots is also extremely important on retaining the soil. As a result, rockfall hazard at a forested slope should be analysed by focusing on both forest characteristics and rockfall dynamics.

When a forest fire occurs, the natural defense of the vegetation is lost. Wildfires cause damage from the tree crown to the roots, and shrubs used to be completely burned. Moreover, the burned roots in the rock joints accelerate physical weathering processes. The effects of the wildfire on the vegetation depends on the intensity and duration of the fire. The total recovery of the environment after a fire can take from a few years to several decades, depending on the weather and the climatic conditions [12]. The critical role of climate change combined with high severity fire is demonstrated, as well as a slower capacity of vegetation recovery after wildfires [45].

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Figure 2. Rockfall boulder ‘catched’ by a pine in *Cala Sant Vincent* (Ibiza, Spain).

3.2. Increase of rockfall occurrence

Regarding geomechanical characteristics, the number of sets of discontinuities that affect the rock mass, as well as the nature of its filling (if any) and the presence or absence of water, stand out first [96]. During a wildfire, these conditions are altered. Furthermore, there is a degradation in the rock matrix properties reducing the rock strength and increasing the fracturing of blocks and the potential to disaggregation of the initial rock mass and breakage of the blocks during the occurrence of rockfall processes (i.e., increase fragmentation potential). The increase of rockfall after a wildfire is not only associated with the effects on the rock mass but also with the loss of vegetation. Dorren et al. [46] explained that trees reduce the energy of the boulders mainly in three ways: rotation and translation over the roots, deformation by their hit in the tree stem, and penetration of the rock in the impact. With regard to these considerations, there is a relation between the type of forest (i.e., DBH or density) and its capacity to hold back boulders of a specific size. Some studies [44, 47] suggest that a forest should account for one-third of the size boulders with the mean DBH, producing a reduction of rockfall velocity in 26% on average and the maximum rebound height by 75% on average.

3.3. Influence on modelling parameters

Numerical modelling can help on determining the rockfall trajectories and estimating the kinematic behaviour of the boulders. The most important input parameters when performing numerical simulations of rockfalls are the restitution coefficients and the dynamic friction coefficients. The first one depends basically on the angle of impact and the properties of the soil, and the second one determines the force in the opposite direction of the sliding of the block. The value of the friction coefficient depends not only on the shape of the rock but also on the characteristics of the surface of the slope. Both coefficients quantify control of the amount of energy lost during the impact of a block over the slope surface. The estimation of restitution and friction coefficients is a complex task still not standardised. This is due to the difficulty in calibrating and validating the soil parameters in the models. In any case, if the simulation is carried out in a burned area, the effect of the fire is a factor that must be taken into account. Wildfires induced impacts on soil properties. The severity of these impacts depends on the duration, intensity, and frequency of the fires [48]. In the case of low-intensity, fires in which the temperatures reached are not very high, the effect on the vegetation is low

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and only the outermost layer of soil is affected. However, during high-intensity fires, in which the temperatures reached are higher, there is an important removal of the vegetation coverage which can lead to important alterations in the properties of the soil.

Nevertheless, literature on the modelling of rockfalls shows that few studies take into account how the restitution coefficients and the dynamic friction coefficient change after wildfires. Sabatatakis et al. [49] estimated the values of the restitution coefficients in five cases in western Greece, showing the influence of the loss of vegetation, founding values that are reduced by 15% to 25% after the fire.

4. Potential affection during and after wildfire

4.1. Firefighting activities and rockfalls

Wildfire fighting is a hazardous activity. Despite the fact that many studies are made regarding on exposure for firefighters during a fire extinction to gases or temperature, little is known regarding the exposure of firefighters to rockfalls. The main statistic to evaluate the effect of rockfalls in firefighting activities is the number of fatalities. In the US, data provided by U.S. Fire Administration (USFA) shows a general upward trend in deaths of fightfighters. In the period of January 2000 to October 2019, there were 99 fatal injuries in wildland fires. Regarding the cause of fatal injury, 32.3% of the fatalities are by caught or trapped. 23.2% of the fatalities is due to collision of vehicle and 20.2% of them by stress/overexertion. Nevertheless, the fourth cause of fatalities are related to struck by elements such as rocks or trees (16.2%). Almost 70% of these deaths occurred during extinction of the wildfire [50].

In Spain, there is a lack of information about firefighter fatalities; the official information records 3 deaths caused by rockfall impacts during the last 10 years [51]. According to direct information from Spanish firefighters, some actions developed during firefighting can trigger rockfalls. The main causes are: a) the destabilization of boulders due to the stretching of the hose lines; b) the movement of firefighting equipment (e.g. fire trucks) and personnel near slope edges or on slopes; c) the impact of water projection on slopes and cliffs by hoses or aerial forest fire-fighting means.

4.2. Impact on infrastructures

The vulnerability to rockfalls can be evaluated for different types of elements at risk: population, buildings, infrastructures, environmental areas or cultural heritage. To do this, the characteristics of these processes, triggering factors and spatial and temporal distribution of the rockfalls have to be known. In many cases, protection elements are used to deal with rockfalls risk: bolt fixing, cable netting, shotcrete or rockfall protective barriers (which usually include systems of cables, anchors and energy dissipators).

However, when a fire occurs, the already referred protective measures can be affected by the high temperatures reached. One of the main effect of wildfire on rockfall protection barriers is the afection of the cables and energy dissipators, changing their properties of friction/tightening with cable ties. In that cases. cables, energy dissipators and nets need to be replaced. High temperatures can also affect nets and bolts making them more brittle and weak, depending on the composition of these elements and the temperature reached during the wildfire.

5. Concluding remarks

Wildfires can induce physical and chemical changes on the rock masses, increasing rock–fragmentation and decreasing rock and discontinuity strength.

Rockfall trajectory (runout) is also modified when the vegetation is lost. Forests are extremely important to protect against rockfalls, as trees reduce the velocity and the rebound heights of the falling rocks. In rockfall modeling, the loss of vegetation tends to change the input parameters, in particular the restitution coefficients. Comparing pre- and post-fire simulations would be an effective tool to evaluate the new hazard of the slope.

Specific attention should be paid to match the characteristics of the wildfire (intensity, duration, etc.) with the rockfalls. Mapping fire intensity and burn severity in combination with the rockfall inventory (pre- and post-wildfire) would help to understand their correlation.

Stabilization and protection measures can be greatly deteriorated by the high temperatures and may lose their functionality. Furthermore, social risk awareness is increased after a wildfire, and people demand new, urgent and expensive protecting measures.

In addition, firefighting actions can increase the rockfall activity. Firefighters and emergency authorities should develop strategies for rockfall risk reduction during wildfires in collaboration with the scientific community.

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