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Assessment and management of cascading effects triggering forest fires

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Abstract
A crisis situation may be due to the occurrence of a single hazard event with large impacts or due to several hazard events occurring simultaneously. Hazard events occurring at the same time may have independent causes or may result from a sequence of triggering effects. The outcome of a situation for which an adverse event triggers one or more sequential events is generally called "cascading effects".
The perception and understanding of the potential occurrence of cascading effects is of great relevance for planning and response activities since an unexpected scenario in an emergency may worsen the situation endangering people, goods, and may nullify a strategy that was developed accounting for a scenario in which the triggering event was considered as a single occurrence.
This paper presents an analysis of possible scenarios of cascading effects triggered by an earthquake. A detailed quantitative example in which an earthquake causing an electric cable failure that potentially ignites a fire is presented. In particular, a methodology to assess the occurrence probability of the event chain earthquake→cable failure→fire ignition is presented. The final results are presented as conditional probability maps representing each transition, namely: earthquake→cable failure, cable failure→fire ignition, and the assessment of the full path earthquake→cable failure→fire ignition.
This study is a part of a pilot application built to test the integrated crisis management system which is being developed in the FP7 European Integrated Project – CRISMA ("Modelling crisis management for improved action and preparedness").

Keywords*: Forest fire; earthquake, multi risk assessment; multi-hazards, cascading effects, domino effects.*

1. Introduction

Similarly to other natural and man-made hazard events forest fires can be triggered by some other event or they can themselves trigger one or more hazard events in a situation that is designated by a cascading effect (Marzocchi *et al.*, 2009, 2012). In a cascading process we may have either a series of events occurring in sequence or in parallel at the same time. From the operational and management points of view, the possibility of having cascading effects involving forest fires as triggering or triggered event are of great importance for the following reasons:

- The response forces will have to face two or more simultaneous or sequential events of different nature requiring a distribution of human and material resources;
- The possible diversity of events occurring in a cascading effect scenario claim for a respective versatility of the crisis response system;
- It may be possible that the strategies designed to respond to a single hazard event are not feasible due to the triggering hazard event(s).

For these reasons, it is important to investigate and assess the risk of cascading effects scenarios that may trigger forest fires, in order to improve mitigation procedures and preparation activities, but also to reduce impacts.

In this paper we explore scenarios of cascading event in which forest fires triggered after earthquakes (EQ) are studied and propose a probabilistic framework for their assessment. The presented example is based on the simulation of an EQ occurring in the surroundings of L'Aquila province, in the Italian region of Abruzzo. The spatial domain used for the analyses is shown in Figure 1. This area was affected by a Mw6.3 EQ in 2009 (Pondrelli *et al.*, 2010). This event caused 308 victims, 1,500 injured and the temporary evacuation of more than 65,000 people from their houses in L'Aquila and surrounding municipalities (Alexander and Magni, 2013). Several aftershocks were felt after the main shock compromising the rescue operations. All the available civil protection authorities were allocated in these response efforts. In the proposed scenario the situation is even more stressed assuming the possible occurrence of a forest fire due to damages to the electricity network (cable failure) caused by the EQs. It is assumed that the forest fire spreads in the direction of a village threatening the population, the houses and other assets. An efficient distribution of human resources and equipment is required to face the two interconnected disasters. In addition to earthquake induced risk for people inside houses, also the possibility that people cannot stay outdoors is to be considered because the village can became immersed in smoke. Several options are highlighted and a multi-criteria analysis, based on pre-defined indicators, criteria and costs, is carried out in order to find the most efficient way to deal with the situation.

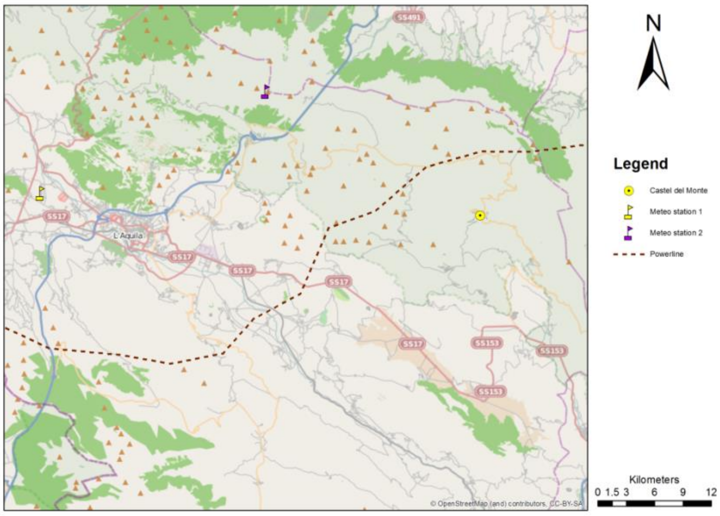

Figure 1. Map showing the area of interest for the study. The location of a hypothetical power line considered for the scenario assessment is also presented.

The analysed scenario refers to a pilot application of the EU-FP7 CRISMA Project. CRISMA focuses on large scale crisis scenarios with immediate and extended human, societal, structural and economic, often irreversible, consequences and impacts. The developed Integrated Crisis Management Simulation System (ICMS) is a simulation-based decision support system for modelling crisis management, improved action and preparedness. In this paper only the part directly related to the cascading effects of the described scenario will be elaborated on.

The methodology herein described for the probabilistic assessment of cascading effects scenarios begins with the selection of the event chain to be assessed. The first step is to identify and to structure the possible event chains and select those of interest for quantitative analyses. The result of this process is illustrated in Figure 2. In this study we focus our attention on the event chain earthquake (EQ)→cable failure (CF)→fire ignition (FI). After selecting an event chain of interest, all the necessary input parameters need to be identified and calculated in order to produce information on the occurrence probability for the scenario(s) of interest. In this case, it is necessary to calculate the following conditional probabilities (hereinafter called "transition probabilities"): EQ→CF: $p(CF|PGA)$, where PGA (peak ground acceleration) is an example of intensity measure used to characterize the EQ hazard, and CF→FI: $p(FI|CF)$. Using this information is therefore possible to calculate the probability of occurrence of the scenario EQ→CF→FI. The outputs are provided as probability maps in order to facilitate interpretation.

Once the most problematic spots are identified, new simulations may be carried out in order to evaluate the importance of the triggered events. Some indicators may be produced to compare different scenarios and to support the final decisions. These last tasks are a consequence of the cascading effects evaluation and some examples are given in this paper.

2. Structuring scenarios: the event chains database

After the implementation of a detailed procedure for scenario identification and structuring, a database with various identified possible cascading event chains was created for a set of triggering events, including earthquakes (Figure 2). The sequence of events is often cyclic as a certain event type may occur in the same chain more than once. This repetition may be direct (e.g. EQ→EQ) or indirect (e.g. forest fire →WUI/urban fire →Forest fire). When a potential cycle is verified, the symbol … was used to indicate the cyclic chain.

The possibility to have certain scenarios strongly depends on the specific case under analysis. For example, the possibility of having an explosion triggered by damages to an industrial facility depends on the type of industrial facility damaged in the area of interest. Under this perspective, the proposed diagrams must be adapted to the characteristics of the hazard event and to the area of interest.

The event chains database is of great importance as it allows the choice of the path of interest and the cascade event analysis that shall be performed. The quantitative example in this paper is centred in the specific scenario of an EQ causing damage to the electricity network (cable failure), leading to fire ignition and triggering a forest fire. In this demonstrative scenario, a Mw5.6 EQ occurring in the NE part of the study area was simulated as the triggering event. In the considered scenario, the EQ may provoke damages to the electricity network, specifically to the cables joints/couplings devices (Figure 3a) near to the pole, which may cause a rupture in the electric cable. As this electric cable is energized, it may ionize the air to the ground and consequently an electric discharge may occur. Figure 3b shows an example of air ionization caused by the proximity of a tree branch and Figure 3c shows a fire ignition caused by an electric discharge. Both examples follow the same principle of the application managed in this paper, however in this scenario we consider the case in which the area reached by the electric arc is covered by surface fine forest fuels where it is possible to trigger an ignition that may develop to a forest fire.

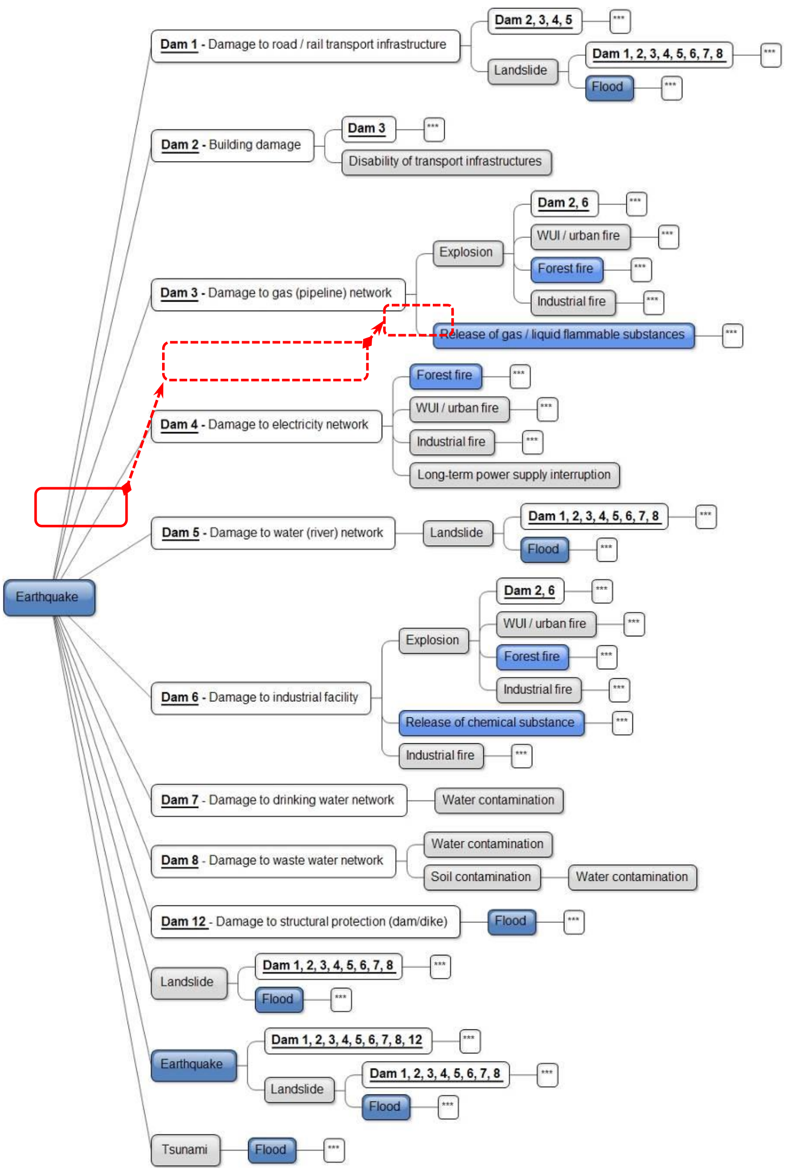

Figure 2. Diagram of the identified cascade event chains for Earthquake

Figure 3. Images showing an example of electric poles, electric discharge, and fire ignition. (a) Detail of a cable joint/coupling; (b) example of air ionization caused by the proximity of a tree branch; (c) fire ignition caused by an electric discharge.

3. Quantitative data analysis

In this section we assess the occurrence probability of the selected scenario. To assess the scenario of interest, different input information is required, namely information related to the initial world state and information about the probabilities for the occurrence of transition between events. As "world state", in CRISMA, we understand a particular status of the world, defined in the space of parameters describing the situation in a crisis management simulation that represents a snapshot (situation) along the crisis evolvement (Almeida *et al.*, 2014). The change of world state, that may be triggered by simulation or manipulation activities, corresponds to a change of (part of) its data contents.
After the triggering EQ event, the initial world state changes as a consequence of the impacts resulting from it. Some impacted elements may be vulnerable in a time-dependent manner; therefore, the word state may in fact be considered to be continuously changing after the triggering event. Nevertheless, to assess the possibility of cascading effects, the world state at each moment exactly before a plausible triggering effect must be identified.
The transition probabilities are the conditional probabilities required to determine the likelihood of a transition, and primarily depend on the intensity of the triggering events in the chain.
Figure 4 schematically presents the flow of information necessary for the quantitative assessment of the event chain of interest in this work. Besides the probability functions regarding the fragility curve of the electric system and the probability of ignition after the electric cable failure, other three categories of inputs must be previously available in the world state. These are the location of the electricity network (Figure 1), the intensity distribution (shake map) of the EQ (Figure 5), and the fuel cover in the area of interest (Figure 6).

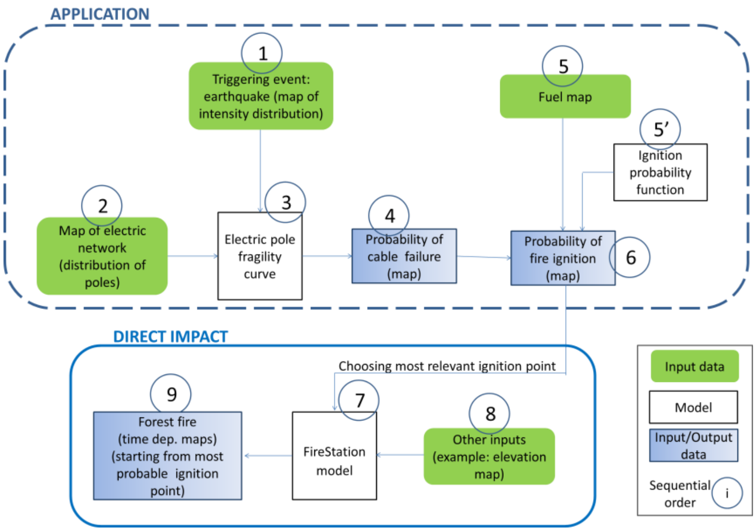

Figure 4. Flow of information necessary for the computation of the selected cascading effects scenario.

The conditional probability of a cable failure in the electric system given the EQ occurrence (and the consequent formation of an electric arc) is estimated considering the intensity distribution of the EQ (shake map) and the fragility function of the electric pole. The intensity of the EQ along the electric network is calculated using regional ground motion prediction equations that provide the intensity measure (in PGA or macro seismic intensity) at each electric pole position. On the other hand, the fragility function relating the intensity of the earthquake to the probability of cable rupture is calculated attaining a limit value of displacement at the pole top varying the intensity of the seismic input. The probability of an ignition started by an electric discharge is estimated considering the fuel classification of the area where the electricity cable failure occurs and the associated ignition model. The fuel classification is part of the world state and is available in form of a fuel map of the area of interest (Figure 6). If the electric discharge occurs in a non-fuel area, as for example a road, the probability of ignition is zero. However, if the electric discharge occurs in a fuel area, as for example a grass land, the probability of ignition is determined by using the ignition probability model described in Section 3.2.2.

If we address the whole event chain (i.e. EQ-DEN-FI), the probability of a fire ignition due to an EQ is given by the product of the respective conditional probabilities at each node of the sequence, i.e., the probability of fire ignition given an electric cable failure, $p(FI|CF)$, the electric cable failure probability given the intensity of the ground shaking, $p(CF|PGA)$, and the probability of observing the EQ intensity, $p(PGA)$. Note that in this example we do not consider uncertainties in the ground motion prediction equation used and therefore $p(PGA)$ is assumed to be 1.

3.1. Input data

Location of the electric network

The location of the hypothetical electric network considered in this study is presented in Figure 1 and was defined at the most opportune location, only taking precautions to not locate a pole in an unlikely place such as in the middle of a river. The separation between two successive poles is 300m.

Map of EQ intensity distribution

The occurrence of a Mw5.6 EQ in the NE part of the study area has been simulated as the triggering event for this scenario. The shake map of this event, represented by the intensity of the ground motion in the area of interest, is shown inFigure 5. Using that shake map, the peak ground acceleration (PGA, in %g) is calculated at the base of each pole of the electric network considered for this study.

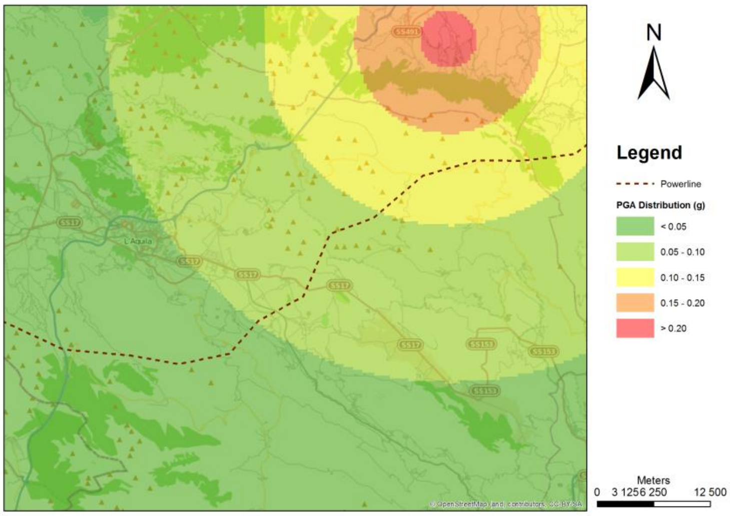

Figure 5. Map of the triggering earthquake intensity distribution with location of the electric power network (distribution lines - smaller poles)

Fuel map

The fuel map is crucial to evaluate the probability of ignition as it includes the information on the class of fuel in the cell(s) where each electricity pole is located. To be harmonized with the fire behaviour prediction model used (FireStation, Lopes *et al.*, 2002), the classes defined in the fuel map are consistent with those used in the FireStation model. As can be seen in Figure 6, in the area of interest there are seven different fuel classes, with grassland being most prominent.

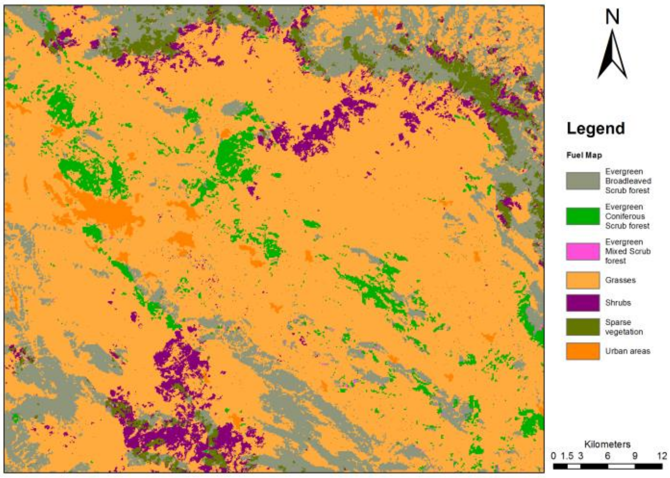

Figure 6. Fuel map for the region of L'Aquila. This fuel map was developed in April 2014 by the ArcFUEL Project Consortium from a cooperation protocol established between CRISMA Project and the European LIFE+ Project ArcFUEL.

3.2. Conditional probabilities

Each event transition requires a conditional probability. In the example herein presented, the event "damage to electricity network" is caused by an electric cable disruption (cable failure). However, the same event could also be caused by the fall of a pole. These two different cases require two different probability functions.

3.2.1. *Transition probability function for the cable failure triggered by an earthquake*

The fragility of the electricity poles used in electricity distribution lines is dependent on several factors as their dimensions, material, state of maintenance, etc. The fragility curve represents the probability of cable rupture as a function of the displacement at the pole top varying with the intensity of the seismic input. Such limit value is represented as a fraction of a displacement X_{MAX} (three hypotheses are considered: 0.5 X_{MAX}, X_{MAX} and 1.25 X_{MAX}), where X_{MAX} is defined as the displacement corresponding to the static application of a transversal force. The shaking of a pole may lead to tensions in the cables which may consequently disrupt. Cable disruption normally occurs in the connections which are the most fragile parts of the network.

In Figure 7, the fragility curve of a pole (type: 12B14) as function of the peak ground acceleration (PGA) is shown. In order to simplify the use case, all the electricity poles in the study area will follow the fragility curve X_{MAX}.

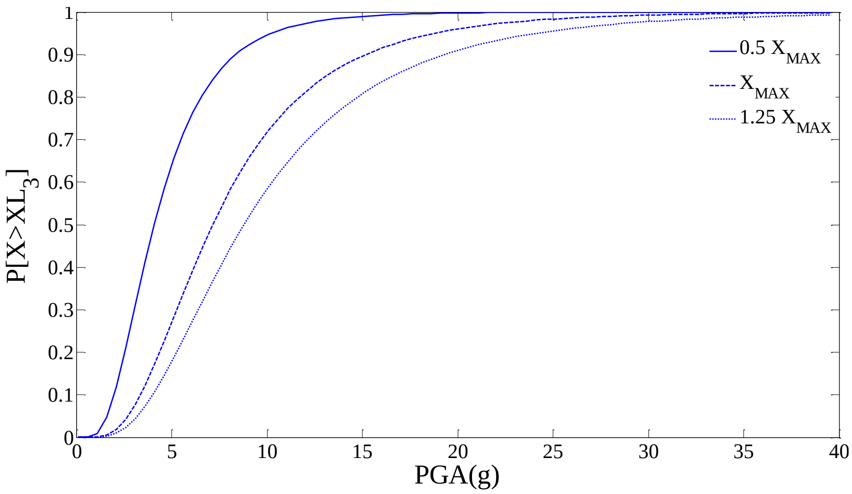

Figure 7. Fragility curves of electric poles to a transversal force T1.

3.2.2. *Transition probability function for fire ignition triggered by cable failure*

The transition from the electric cable failure to a fire ignition has two evolutionary steps: 1) the production of the electric arc from the electricity cable to the fuel bed, and 2) the ignition of the fuel bed by the electric arc.

It is assumed that the failure of an electric cable imperatively causes an electric arc. Due to the existing protection systems, the electric charge is normally interrupted in case of failure and after that, for brief instants, the residual electric charge continues flowing. After the cable breakage, the cable takes some time to land or to reach a sufficient distance to establish the electric arc. The time to ignition by electric arc with high voltage is very short (tenths of seconds) and therefore in this sense it is reasonable to consider the production of an electric arc for a short period as inevitable. On the other hand, the time to ionize the air path from the cable failure to the fuel bed and the consequent production of the electric arc is strongly dependent on the distance and on the resistance of this path. This dependency is a function of many additional factors such as topography, cable height, air humidity, and pressure. For simplification reasons we will not take those aspects into consideration in this paper, but rather assume that the cable failure will always drive to an electric arc that reaches the fuel bed.

In a laboratory environment, several tests were carried out in order to determine the total amount of energy required to ignite a certain amount of fuel. These tests were performed for straw and pine needles (*Pinus pinaster*) for a range of fuel moisture content (FMC) between 9.2% and 12.2%. A bouquet of the fuel material was exposed to an industrial electrical arc of certain power (P [kVA]) as can be seen in Figure 8. The time (t [s]) elapsed from the beginning of discharge until the evidence of combustion was measured. The energy (E[kJ]) required for ignition was determined using Equation 1.

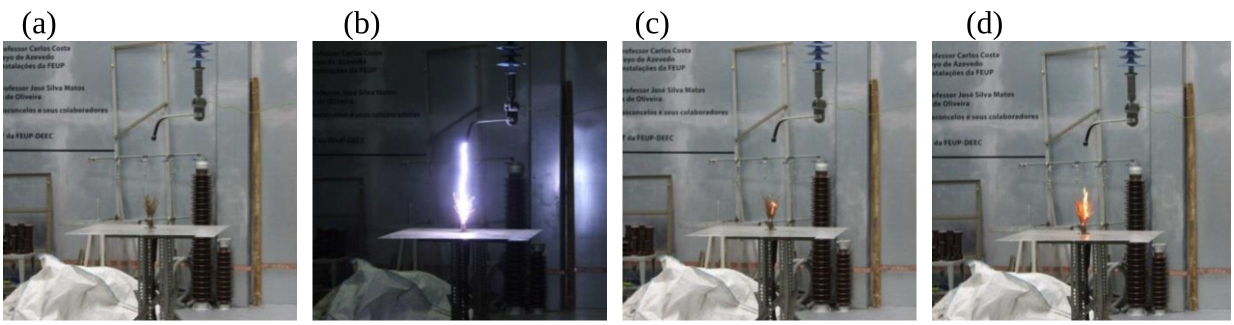

Figure 8. ***Sequence of images of a laboratorial test to determine the energy required for ignition by industrial electric discharge.***

$$E = P \times t \qquad \textbf{[1]}$$

It was found that the probability of ignition was not significantly different for the several tests at different conditions of FMC or different types of fuel (straw or pine needles) and also the fuel load does not seem really relevant for the probability of ignition. This statement should be considered preliminary since not many tests with fuels other than straw and pine needles were carried out and the range of fuel moisture content was not very extensive. It also refers specifically to the situation of a cascading effect scenario, i.e. the possible spot ignition by electric discharge. Findings might be different for other ignition causes where fuel and soil moisture are expected to play a more significant role and are therefore sometimes regionally monitored to identify and address potential susceptible areas (Aubrecht *et al*., 2011).

Using the data collected in the laboratory experiments, we estimated the parameter of different competing probabilistic models in order to find the distribution providing the best description of the laboratory observations. As possible competing models we used the Log-normal, Gamma, Normal, Weibull and Exponential distributions. We estimate the model parameters for each candidate model using a Maximum Likelihood Estimate (MLE) approach, and use the Akaike Information criteria (AIC, Akaike 1974) for the model selection. The AIC is a tool based on the concept of entropy and offers a relative measure of the information lost when a given model is used to describe some data (a trade off between accuracy and complexity of the model).

Table 1 summarizes the functional form of the PDF, estimated (MLE) parameters (and uncertainties), and the AIC for all the probabilistic models considered. Using a Kolmogorov–Smirnov test, we cannot reject the Log-normal, Gamma, and Normal hypotheses (at significance level of 0.05), which means that, from a statistical point of view, all these probability models successfully explain the observed data. However, according with the AIC values, the preferred model (i.e. that with the lowest AIC value) is the Log-normal.

Table 1. Candidate distributions, PDF, estimated (MLE) model parameters and uncertainties, and Akaike Information Criteria (AIC). According to the AIC information, the model that best describes the data is the Lognormal

Model	**Probability density**	**Parameters (MLE)**	**AIC**
Log-normal (μ,σ)	$y = f(x\|\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}$	μ=6.334 [6.329,6.339] σ=0.246 [0.243,0.250]	– 62803
Gamma (a,b)	$y = f(x\|a,b) = \frac{1}{b^a \Gamma(a)} x^{a-1} e^{-\frac{x}{b}}$	a=16.68 [16.22,17.14] b=34.84 [33.87,35.83]	– 62845
Normal (μ,σ)	$y = f(x\|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$	μ=581.0 [578.1,583.8] σ=146.3 [144.2,148.3]	– 63319
Weibull (a,b)	$y = f(x\|a,b) = \frac{b}{a}\left(\frac{x}{a}\right)^{b-1} e^{-\left(\frac{x}{a}\right)^b}$	a=637.1 [633.7,640.6] b=3.87 [3.81,3.92]	– 63832
Exponential (μ)	$y = f(x\|\mu) = \frac{1}{\mu} e^{-\frac{x}{\mu}}$	μ=581.0 [569.7,592.6]	– 72815

Figure 9a shows the cumulative probability (CDF) of the candidate distributions and the empirical CDF of the observed data, while the Figure 9b shows the CDF and related uncertainties of the Log-normal model.

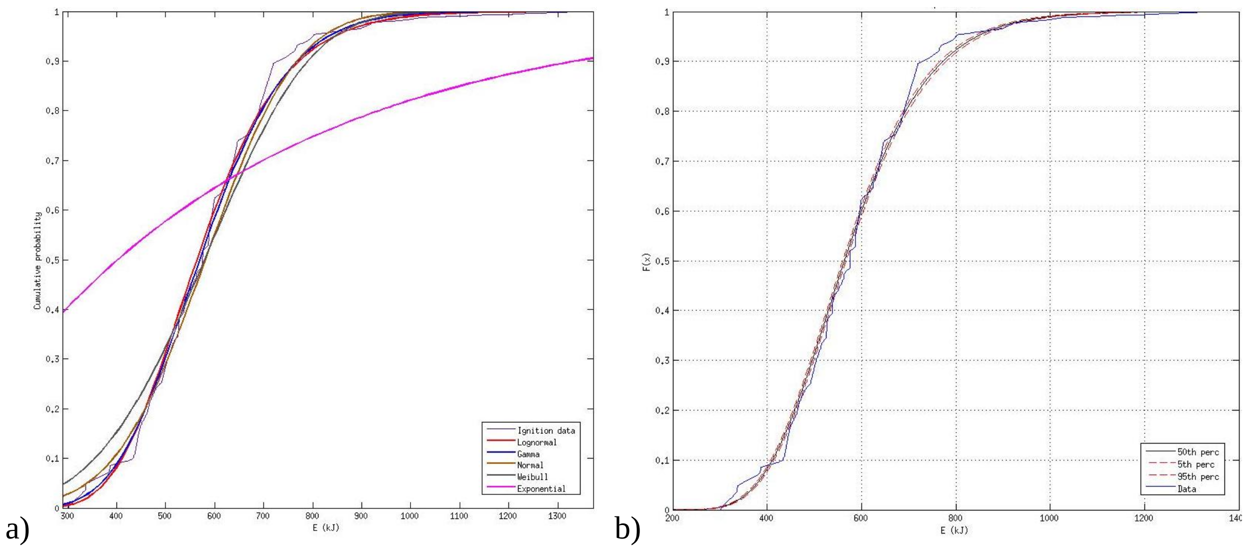

Figure 9. a) Plot of the Cumulative Distribution Function (CDF) of Log-normal, Gamma, Normal, Weibull, and Exponential competing models, and the empirical CDF of the observed data; b) CDF of the Log-normal (with parameters as those presented in Table XX), selected as the best model describing the observations

Therefore, the model selected to describe the energy required to start an ignition is a Log-normal with parameters μ=6.334 [6.329, 6.339] and σ=0.246 [0.243, 0.250], where the values in parenthesis represent uncertainty bounds. The Log-normal model is therefore used for the determination of the probability of fire ignition given the occurrence of an electric discharge. Since for simplicity we consider that an electric cable failure will always generate an electric discharge, this model consequently also represents the probability of a fire ignition given a cable failure.

As previously mentioned, there was no significant difference in the results achieved for pine needles as compared to straw. Therefore, for simplification, we assume that the model can provide the probability of ignition for all fuel classes other than urban areas, where the probability of ignition by electric discharge is assumed to be zero. This assumption seems reasonable as commonly, for prevention reasons, the area below electric cables is cleaned of heavy fuels.

4. Results

In this section, the maps summarizing the results obtained for event probabilities at different parts of the event chain are presented. Figure 10a shows the map representing the probability of cable failure in the electric network given the occurrence of a Mw5.6 seismic event in the NE part of the study area.

(a) (b)

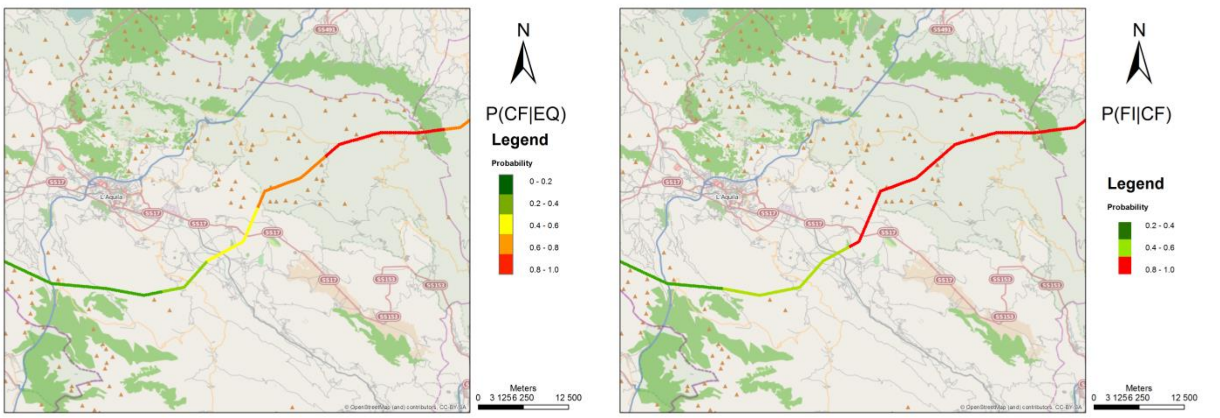

Figure 10. Maps for: a) probability of cable failure, and b) probability of fire ignition due to an electric cable failure

As it was previously explained, cable failures occur close to the electric poles. Therefore, the information on the cable failure probability is presented around the poles. In this case, a single electric poles fragility curve was used (X_{MAX}=1) and therefore the probability of cable failure depends exclusively on the distance between each pole and the seismic epicentre.
Besides the visualization of the map for probability of cable failure due to the triggering EQ event, the assessment of the probabilities of fire ignition due to cable failure also needs to be considered. This information is provided in the form of a distribution map as shown in Figure 10b. The map for distribution of fire ignition by electric cable failure is obtained from the fuel map (Figure 6), the geographic location of the electric network (Figure 1) and the probability function of fire ignition.
It is worth noting that the probability of fire ignition is strongly dependent on the energy released by the electric discharge. The amount of energy released during the discharge was determined by fixing a trigger time (electric interruption) of 0.1s, a power of 8,000kVA (current of 53A and voltage value of 150kV) and consequently 800kJ of energy for the first 20km of electric line (first 67 poles on the right side of Figure 10b). Furthermore, a withdrawal of 100kJ of energy was assumed due to energy consumption and losses for every 20km of electric line, resulting in a decrease of fire ignition probability along the electric network.
Finally, to evaluate the fire ignition probability given the occurrence of the seismic event, the full path of the selected scenario can be assessed. In this case, the probability of fire ignition is the product of the probability of cable failure due an EQ of a certain seismic intensity distribution, the probability of a fire ignition due to a cable failure (Equation 3), and the probability of having the PGA value calculated at the pole site (which in this case is 1 because we neglect uncertainties in ground motion prediction equations). Figure 11 shows the probability map of fire ignition triggered by the occurrence of the seismic event considered in the worked scenario.

$$p(FI) = p(FI|CF) \times p(CF|PGA) \times p(PGA) \quad \textbf{[3]}$$

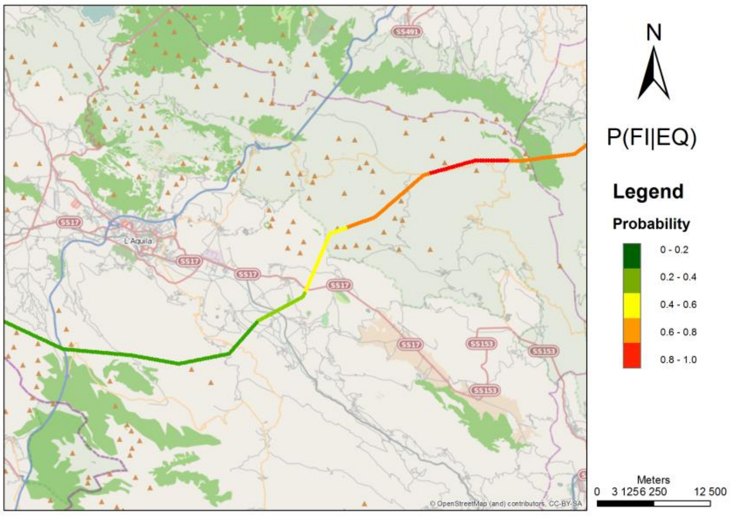

Figure 11. Map for probability of fire ignition due to the Mw5.6 earthquake considered in thestudied scenario

Supported by the information on the probability of a fire ignition around each pole, the simulation of an ignition and the subsequent fire development is commonly the following step. For a given pole with a calculated probability of fire ignition, we perform a fire propagation simulation using the FireStation tool in order to forecast the spread of the fire and other parameters of interest, as shown in Figure 12 The comparison of impacts caused by both EQ and forest fire in a cascade effect event may be an important information to support the decision making process. As outlined by Aubrecht *et al.* (2014), the temporal evolution of the entire cascading effects scenario also provides crucial input for evacuation planning and societal impact assessment, taking into consideration dynamic population exposure models to cover the respective world state states.

(a) (b) (c)

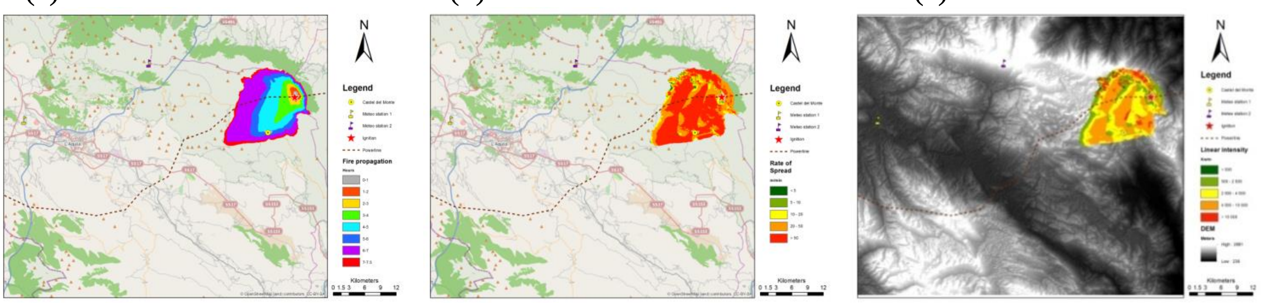

Figure 121 – Map of the evolution of the forest fire (a) after the ignition by the electric discharge from a probable ignition point and other possible outputs from the FireStation software: b) rate of spread, c) linear intensity.

5. Summary

The occurrence of a surprising cascading event chain may complicate an emergency situation caused by the occurrence of an adverse event since the initial strategy may become useless for the new scenario of multiple hazards occurring in a given chain of events. The probabilistic assessment of cascading effect scenarios is therefore of great relevance for precautionary reasons as this evaluation is useful before the hazard transition occurs. The probabilistic assessment of cascading effects scenarios shall be performed in a short and long term planning phase. Short term planning is related to a scenario where the triggering event has occurred and strategic plans are being designed in order to eliminate or mitigate further impacts. Long term planning is associated to a scenario where the triggering hazard event has not yet occurred but plans are being made in advance for preventive or preparative reasons.

A methodology for the probabilistic assessment of cascading effects was described using a sample scenario of an EQ as triggering event. After collecting the reauired data, it was possible to quantify the probability of fire ignition around the electric poles located in the study area. The anticipated perception of the likelihood of secondary events may support decision-making in order to avoid larger impacts caused by the triggered events (as the wild fires considered here) that would cause additional impacts respect to those directly caused by the triggering EQ event.

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