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On the Marginal Cost of the Duration of a Wildfire

Antoine Belgodere^{1*}, Frédéric Allaire², Jean-Baptiste Filippi³, Vivien Mallet² and Florian Guéniot¹

¹*UMR CNRS LISA, Université de Corse, France*

²*INRIA, France*

³*UMR CNRS SPE Université de Corse, France*

ABSTRACT

Avoiding catastrophic wildfires is a natural rationale for fighting fires in their early stage. Beside this benefit, may a marginal decrease in the duration of smaller wildfires be worthwhile? The present article addresses this topic by estimating the marginal damage of the duration of forest fires. We perform two sets of wildfire simulations in Corsica, and estimate the damage based on the type of land use in burned areas. Results suggest that the marginal cost of the duration of fires rises by a factor of 4 during the first 400 minutes. The two reasons appear to be the increase in the marginal burned area (a physical mechanism) and the increase in the value of the marginal burned area, due to the ignition points being located in low-value places (a human mechanism). Using a conservative calibration, our results corroborate the principle of early initial attack already in use in countries with sufficient fire fighting forces, but subject to debate because of its cost.

Keywords: Fire economics, environmental policy, risk assessment, wildfire simulation

*Corresponding author: Antoine Belgodere, belgodere_a@univ-corse.fr. The research presented in this article was funded by French National Research Agency (ANR) as part of the project FireCaster. ANR strictly respects the independence of the authors and does not exercise any control over the published results.

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1. Introduction

Gigantic wildfires, such as the ones that recently devastated large areas of Australia, California, Portugal, Brazil, shed light on the potential dramatic outcomes of an unrestrained fire. In those countries Mediterranean climate and landscapes are among those that suffers the most dramatic consequences, but some countries are barely hit by such massive events. France, for instance, is regularly struck by wildfires, but they remain of size that is manageable by the fire fighting forces. Left panel of Figure 1 presents the maximum fire size in the Mediterranean Departments of France (MDF)¹, which are the most exposed to fires, between 1973 and 2019. Only one year (in 1990) did a single fire burn slightly more than 10 000 hectares. Right panel presents the yearly total area burnt in MDF for the same period. The maximum is reached in 2003 with 600 000 hectares. These are low numbers compared to the 20 000 000 hectares that burnt in 2019-2020 in Australia for instance. France have more than twice (40.000) the amount of career firefighters than Australia (17.000) ², for a much reduced area to protect, and can apply a principle of early initial attack with the benefit of avoiding some of these gigantic events. Is it the only benefit? This paper wants to assess the marginal benefit of reducing the duration of already small fires. Small fires are the submerged parts of the iceberg. 47% of the burnt area in MDF since 1973 have gone up in smoke in fires of less than 400 hectares³, which represent 99.6% of all the events. Even if the marginal cost of fires' size is increasing, it is safe to say that a significant part of the overall cost is due to these small fires. In the context of the present article, the largest simulated fire reaches 13 155 hectares after 8 hours, whereas the largest fire in MDF since 1973 reached 11 580 hectares. Even these extreme values are far from the catastrophic events aforementioned.

The economics of wildfires highlights the needs to balance two types of costs ([19]): i- the expected damage from the fire itself, ii- the different public expenditures aimed at reducing the expected damage, such as prevention, fuel management and suppression. Reducing the duration of fires would decrease the first one and increase the second one. This paper is focused on the damage side of the equation. In other words, if the cost of reducing the duration of a fire by one hour was given, the question we ask in the paper is: "is it worthwhile?" To adress this question, we simulate a large ensemble of wildfires, coupled with land-use data on the island of Corsica, which is a subset of MDF, and represents 36% of the total burnt area since 1973. The land-use data allows to estimate the cost of each fire for each of the 24 20-minute time steps of use

¹Alpes de Haute Provence, Hautes Alpes, Alpes Maritimes, Ardèche, Aude, Bouches du Rhône, Drôme, Corse-du-Sud, Haute-Corse, Gard, Hérault, Lozère, Pyrénées Orientales, Var, Vaucluse

²source: European Commission (European Forest Fire Information System), CTIF, Eurostat, FAO

³This number is set in [5] as the limit between small and big fires. It also corresponds to the fires of categories F and G by the National Wildfire Coordination Group in the USA <https://www.nwcg.gov/term/glossary/size-class-of-fire>

for the simulations.

We anticipate that 2 mechanisms can lead to an increase in the marginal cost of the duration of a fire.

1. a *physical mechanism*: a typical fire tends to burn a higher surface per hour when time increases (at least for the first hours).
2. a *human mechanism*: it is likely that the most valuable places are better guarded and protected against fires than the least ones, so we can expect the ignition points to be located in low-value places. In this case, an increase in duration will tend to increase the value of the burnt areas.

Our main results suggest that:

1. Within the two sets of simulations, the marginal cost of duration significantly increases during the first 400 minutes.
2. In both cases, the increase in the marginal burnt area explains the increase in the marginal cost.
3. In the case of the simulations based on 7 real fires with precise ignition points, the cost of the marginal burnt area sharply increases within the first 300 minutes.
4. In this case, the marginal cost of duration increases at a significantly higher rate in the case of the 50% windiest events, both because of the higher burnt area and the higher cost per hectare of the marginal burnt area.

This research relates to a trend of literature that is devoted to assessing the cost of wildfires. [6], [20] and [1] are three important methodologic contributions. These studies provide clear designs for general cost assessment of wildfires, and apply it to several case studies. Other articles focus on specific impacts such as health problems caused by smoke ([16]) or the impact of wildfires on the housing market ([14]).

None of these pieces of research focus on the marginal cost of the duration of a fire. The reason they don't is that they rely on data related to real consequences of wildfires. These type of data are ex-post data, and typically do not allow researchers to identify the part of the cost of a wildfire that comes from the first hour, the second, etc.

In this paper, on the other hand, we rely on simulations in order to follow the evolution of the cost over time. Each simulated fire is described by a polygon of the burned area every 20 minutes, that allow to estimate a cost, depending on the type of land use in the burned area. The evolution of this cost along the simulation provides an estimate of the marginal cost of duration.

Notice that [13] use simulation tools, but in a very different context: in a field experiment, they show that Virtual Reality representations of wildfires improve the accuracy of policy making.

The paper is organized as follows: Section 2 presents the numerical simulation methods for the evolution of a wildfire and to generate the ensemble of simulations, and presents general data about the simulated fires ; Section 3

describes the method and data of use to predict the cost of a fire with a given contour ; Section 4 presents the main results of simulations ; Section 5 is a discussion section and the last section concludes.

2. Numerical methods and data

2.1. Simulation of wildland fire spread

Knowing how a wildland fire will spread is a key aspect of firefighting as it helps in deciding the most effective actions to stop the fire and/or mitigate its impacts on life and property. With the availability of powerful computational resources, numerical simulation has become an invaluable tool to study and predict wildland fire spread. Models from varying complexity can be used to describe the dynamics of fire propagation and can be classified as (semi-)physical or (semi-)empirical [24]. The former are more comprehensive in the description of the physics of combustion but the resulting simulations are too time-expensive for the computation of very large fires in real time. Meanwhile, fire spread simulators [25] that describe the dynamics of the shape of the fire are faster and more suited to make predictions in an operational context. Such simulators typically make use of an empirical model where the rate of spread (ROS), i.e., the speed at which the flames advance, is expressed as a function of local environmental parameters. Most ROS models take into account wind speed V , slope α , fuel moisture content m (= mass of water / mass of dry fuel), as well as parameters that describe the properties of the vegetation (which is also the fuel), and can be summarized as follows:

$$\frac{dx}{dt} = r(V, \alpha, m, \dots), \quad (1)$$

where x denotes the location of the flames, t denotes time, and r is the ROS function. Usually, the ROS increases with wind speed V and slope α , while higher fuel moisture content m leads to reduced ROS. Equation (1) is inherently 1-dimensional whereas numerical simulators of wildland fire are inherently 2D. In these models, a fire most commonly follows a binary representation where any location in the the landscape is either burned or not burned at a given time. Simulating fire spread therefore amounts to determining the evolution of the burned part of the landscape over time. The interface between burned and not-burned areas is referred to as the *fire front*, and the evolution of a fire can be viewed by displaying the successive states of this interface across the landscape, as depicted in Figure 2.

Fire propagation solver ForeFire [8] is performing the simulations. ForeFire uses a front-tracking technique to model the propagation of the fire front. The fire front is discretized by the means of Lagrangian markers linked by a dynamic mesh. Each marker is advanced according to the surface geometry and the ROS. Here, the latter is computed according to the empirical model of Rothermel [22], widely used in wildland fire simulation, and that contains

numerous parameters already fitted and fixed through an analysis of a large set of laboratory experiments.

Running a simulation relies on several data fields that determine the local environmental parameters from which the ROS will be computed wherever the markers of the fire front are positioned. Slope α is computed from an altitude layer. Wind speed V varies locally due to the spatial variations in the altitude layer but is determined by a single “triggering” value of wind speed vector. This triggering value is obtained from a weather forecast and may be modified at some points in a simulation to account for changes in weather. Fuel moisture content m is derived from the weather forecast and may vary over time in the same fashion as wind speed, but it is constant over the landscape. Another layer is the land cover map, which identifies different fuel types over the landscape. For each of these fuel types exists a corresponding parameterization (a “fuel model”) which determines the remaining input parameters of the ROS used to characterize the vegetation. Areas that are not vegetation (cities, bodies of water, bare rocks, etc.) are not considered as fuel and, therefore, cannot be burned. The remaining inputs that are necessary to run a simulation are a few spatial and temporal pieces of information on the fire, namely the coordinates of the presumed ignition point, which will define a small initial burned area, as well as the time of ignition, and the duration of the fire. The characteristics of the seven fire cases mentioned in the present study can be found in [3], and the interested reader will find more details regarding the data sources used to run the simulations. A major difference to note in is that the present study is focusing on the potential evolution of the cost and are not attempting to compare the simulations to the observed burned surfaces. Here, fires were simulated for a 8 hours duration, regardless of the actual duration of the fire.

2.2. Generation of an ensemble of simulations

In spite of the recent advances in wildland fire spread modeling, making accurate predictions of large fires is still a considerable challenge. Complex physical phenomena among which convection, heat transfer, pyrolysis and combustion, come into play at possibly very small spatial and temporal scales, whereas a fire may spread during several hours or even days, resulting in burned surfaces that can amount to thousands of hectares. This also implies that fire spread may occur in highly variable environmental conditions, as weather, vegetation state, and topography can be considerably different across the landscape and over time. Simulators that are used in an operational context often rely on an incomplete or over-simplified formulation of the underlying physical and numerical model, resulting sometimes in inaccurate predictions.

A major source of uncertainty in wildfire spread prediction relates to the input variables of the simulation. Wind speed, fuel moisture content, fuel parameterization, time and location of fire ignition, as well as fire duration are not known perfectly. The best estimates of these variables may result in a simulation that significantly differs from the observed spread of fire. Instead of relying on a single deterministic simulation, a promising alternative consists in adopting a probabilistic approach where several simulations are run based

on different likely sets of inputs, which results in an ensemble of simulations traducing possible scenarios, as exemplified in Figure 3.

More formally, $\mathcal{S}_{\mathbf{u}}(t)$ is introduced as the burned surface at time t returned by the simulator based on the set of inputs $\mathbf{u} \in \mathbb{R}^d$. Input uncertainty is modeled by attributing a probability distribution $\mathbb{P}_{\mathcal{U}}$ to the inputs, which is now perceived as a random vector \mathbf{U} . The resulting burned surface $\mathcal{S}_{\mathcal{U}}(t)$ is now probabilistic and traduces the probability for any location in the landscape to be burned at time t , according to the simulator and the input uncertainty. In practice, the *burn probability* at time t is estimated by the means of an ensemble of M simulated burned surfaces $\mathcal{S}_{\mathbf{u}_1}(t), \dots, \mathcal{S}_{\mathbf{u}_M}(t)$, where $\mathbf{u}_1, \dots, \mathbf{u}_M$ are sampled independently from the same probability distribution $\mathbb{P}_{\mathcal{U}}$.

Several approaches for ensemble generation are available in the literature [9, 15, 18]. Depending on the study, the uncertain inputs may not be the same and for a commonly identified uncertain input, its marginal probability distribution may also differ. In the present study, the uncertain inputs are those identified in [3], with the exception of time of fire start and time of fire end: here, simulations of fires are systematically run with a fixed duration of 8 hours and fixed time of fire start. Another notable difference is that a *calibrated* probability distribution is used instead of the *a priori* distribution proposed in the aforementioned study. The calibration method is detailed in [4]. The key elements of this calibration procedure consist in using an *a priori* distribution where the marginals have higher variance than in [3] and including the information of observed burned surfaces of the seven large fires mentioned in the present study. The *probability density function* (PDF) g of the calibrated distribution is intended to be higher than the prior PDF f for a given \mathbf{u} when there is good overall agreement between observed burned surface \mathcal{S}_{obs} and corresponding simulated burned surface $\mathcal{S}_{\mathbf{u}}$. More precisely, the PDF g can be expressed as follows:

$$g(\mathbf{u}) = \frac{e^{-\beta E(\mathbf{u})} f(\mathbf{u})}{\int e^{-\beta E(\mathbf{u})} f(\mathbf{u}) d\mathbf{u}}, \quad (2)$$

where $\beta > 0$ and E is a positive “energy” function that is equal to 0 when $\mathcal{S}_{\mathbf{u}} = \mathcal{S}_{\text{obs}}$ for each fire and increases with the dissimilarity between simulated and observed burned surfaces. Measurement of shape dissimilarity relies on the Wasserstein distance, which is a metric that appears in the field of optimal transport (see, for instance, [23] for an extensive review), and $E(\mathbf{u})$ can be understood as an energy that is required to transform $\mathcal{S}_{\mathbf{u}}$ into \mathcal{S}_{obs} . The definition of g is inspired from Bayes’ rule:

$$p(\mathbf{u}|\mathcal{S}_{\text{obs}}) = \frac{\mathcal{L}(\mathcal{S}_{\text{obs}}|\mathbf{u})f(\mathbf{u})}{\int \mathcal{L}(\mathcal{S}_{\text{obs}}|\mathbf{u})f(\mathbf{u})d\mathbf{u}}, \quad (3)$$

where $p(\cdot|\mathcal{S}_{\text{obs}})$ is the posterior PDF that would be obtained from $\mathcal{L}(\mathcal{S}_{\text{obs}}|\cdot)$, the likelihood of the observation, and f , the prior PDF. The exponential in Equation (2) can therefore be seen as a pseudo-likelihood function, whose weight increases with the parameter β . When $\beta = 0$, the calibrated PDF g is equal to

the prior PDF f and $\beta = 1/2$ in the present study.

2.3. Fire Data

The simulations described in the previous paragraphs are run to reproduce wildfires from Corsica. Unfortunately, the official database Prométhée⁴ that lists all the fires in MDF since 1973 does not allow to properly account for the ignition points. Indeed, the ignition point is given in DFCI coordinate system, made of 5 polygons within a $2\text{km} \times 2\text{km}$ square (see figure 4 and https://geoservices.ign.fr/blog/2018/03/26/carroyages_DFCI.html for a presentation in French), and the ignition time is often arbitrarily set to midnight. As a consequence, we are not able to simulate the evolution of the cost of fires with both i- precise ignition points to account for the human choices of time and place to burn, and ii- a sufficiently high number of cases to provide statistically reliable results.

We overcome this difficulty by performing two different sets of simulations. For the first set, we retrieved meteorological conditions and ignition points for each of the 7 biggest real fires that took place in Corsica between 2017 and 2018 to account for the simulation of realistic fires. These 7 events happened after the start of this research, which allowed us to retrieve precise data on: i- the ignition points and times, via a close relationship with the fire fighting services, and ii- on the meteorological conditions, via Météo France. For each of these 7 fires, an ensemble of 500 simulations are run, that each differ due to random variations in the meteorological parameters, in the precise ignition point, as well as in fuel parameters. These variations were calibrated so that they maximize the likelihood of the simulated events [3] and provide significantly variable outcomes.

For the second set of simulations, we use 933 approximate ignition points referenced in Promethee database for fires of more than 10 hectares (after removing those falling into the sea) and we simulate 14 fires for each of this points corresponding to 14 extreme meteorological conditions experienced in Corsica between 2017 and 2019⁵. These simulations clearly lack the precision that would allow to account for the aforementioned *human mechanism* (higher prevention in high value places). So we expect this mechanism to be invisible in these simulations. On the other hand, these simulations will be more reliable to account for the *physical mechanism* due to the increase in the marginal burnt area.

In each case, the cost of the fire is estimated at a fixed time step for each simulation by using reasonable cost parameters for each type of land use. If no firefighting actions are provided, the simulated fire will continue to spread until it reaches nonburnable land, requiring an external criterion to stop the computation. In the current set-up, simulation is set to stop at a given fire duration. For each simulation, the fire shape is sampled every 20 minutes until it reaches 8 hours. The resulting simulations are pooled to perform cost estimates

⁴<https://www.promethee.com/>

⁵7 of these conditions are those of the 7 fires of the first set of simulations.

in order to assess the marginal i- cost of duration, ii- the marginal burned area and iii- the cost per hectare of the marginal burned area, controlling for moisture and wind speed.

3. Evaluating the cost of fire

This section describes the procedure to assess the impact of a fire. Assessing the cost of a fire requires collecting data on land use in endangered areas. Especially, it is required to identify the areas containing buildings, agricultural lands, and human beings in the middle of the wild. Then to attribute a value that is likely to be lost in case the fire reaches a given place. Finally, adding a risk premium to the expected cost of a given fire in order to account for risk aversion.

3.1. Land Use in Corsica

Representations of land use in Corsica is decomposed into 6 rasters of $85.5\text{km} \times 183.3\text{km}$ with a resolution of 50 meters with:

1. Buildings. *BD-topo* by the French *Institut National de Géographie* (IGN)⁶ provides vector data on all identified buildings in Corsica. Each cell's value is the sum of the areas it contains expressed in square meter.
2. Remarkable buildings. Some of the buildings are deemed remarkable by IGN. These include churches, castles, city halls... These buildings are already included in the building raster. The remarkable building raster assigns to each cell the number of remarkable buildings it contains.
3. Agricultural lands. The database *Registre Parcellaire Graphique* (RPG) by IGN and the *Agence de Service et de Paiement* (ASP) provides vector data on agricultural lands, with distinct types of cultures (wheat, corn, olives, orchards...). The raster of agricultural lands simply assigns to each cell the corresponding type of culture.
4. Forests. The database *BD-Forêts* by IGN provides vector data on forests. Forests is considered as homogeneous, with a procedure similar as the agriculture class: in each cell indicates the type of forest (deciduous trees, chestnut trees, pines...)
5. Campsites: Corsica is an important tourist destination, with about 3 million tourists each year⁷ for less than 400 000 inhabitants⁸. OpenStreetMap provides a list of campsites represented by dots. With no information on the size of these sites, a campsite is assumed to expand over a $250 \times 250\text{m}^2$ square, which corresponds to the cell where the dot is located plus the 24

⁶IGN changed its name in 2012 for *Institut national de l'information géographique et forestière* commonly called IGN

⁷source: Agence du Tourisme de la Corse <https://www.corsica-pro.com/fr/observatoire/chiffres-cles>

⁸335 000 in 2017 according to INSEE https://www.insee.fr/fr/statistiques/fichier/version-html/4271414/co_inf_46.pdf

cells around this one. The number assigned to each cell in the raster file corresponds to the share of campsites it contains. If a single site expands over a given cell, the cell will be assigned the value 0.04 (1/25). In the case of two sites that are close neighbors, cell that contains both sites will be assigned the value 0.08.

6. Hiking paths: we represent hiking paths listed by the Corsican natural reserve⁹ as poly-lines. When such a poly-line crosses a given cell, value of 50 linear meters of path is assigned, which corresponds to the length of the square it represents¹⁰.

For each of these rasters, a value must be assigned to each cell in order to assess the economic value at risk in case the corresponding area is burnt.

3.2. Cost of a single fire

For all categories of cost, the actual cost of a fire strongly depends on fire intensity. If a house is completely destroyed by a fire, then it sounds wise to assess the cost of the fire as being equal to the cost of rebuilding the house. This represents the maximum cost that can be born by the householder¹¹. However, damage will, hopefully, often be much lower than this maximum value (for instance, only the roof can be burnt). The strategy followed to estimate the cost of a fire consists in: i- estimating the maximum cost based on the type of land use, ii- multiplying this maximum by a scaling factor $s \in]0; 1[$ chosen so as to produce correct orders of magnitude. Identifying correct orders of magnitude proves to be complex for two reasons:

First, there is a large variability of estimates in the literature. For instance, [1] estimate the costs of 4 fires that took place around 2000 and find costs that range from \$300 to nearly \$18 000 per hectare. [17] have narrower estimates for 3 other fires (between \$1000 and \$5600 per hectare). The tiny literature on the topic does not allow to perform multivariate analysis in order to identify the determinants of this variability.

Second, the literature based on real cases presumably focuses on costly fires, whereas this paper aims at accounting for fires of all degrees of severeness.

With this unavoidable limitations in mind, $s = 0.01$ was chosen, which results in a median cost of €130.85, a mean cost of €637.65 and a standard deviation of €2264.72¹². Clearly, the level of the estimated cost that calculated hereafter are very sensitive to this somehow arbitrary scaling parameter. However, these results fall into the (wide) range of the estimated costs per hectare of real-life fires comforting this choice. Moreover, it is important to stress that the evolution of the marginal cost of duration over time, and especially the doubling of this marginal cost after 5 hours, is independent from this choice.

⁹Parc Naturel Régional de Corse

¹⁰This length is assumed as an average, since intersections cannot be evaluated at a lower resolution than the raster.

¹¹except for psychological costs.

¹²those numbers include each of the 24 time steps of the 3500 simulations for the 7 fires

Land use	Unit	Parameter value
Forests	€ per hectare	€500
Agriculture	€ per hectare	from €28 to €91.9K
Buildings	€ per built square meter	€1000
Remarkable buildings	additional € per building	€50 000
Value of human life (campsites and hiking paths)	€ per life	€3 000 000

Table 1: List of parameters used to estimate the maximum value at risk for the different land uses.

Table 1 presents the coefficients of use to evaluate the endangered economic value of the fires. Here is a brief justification of these choices:

Forests

Forests cover 58% of Corsican landscape. Yet, commercial use of local timber is limited due to transportation difficulties ([11]). Of course, that doesn't mean that the forest is without value. It certainly have a patrimonial value for Corsican people, and a recreational value, both for local people and for tourists. [2] estimate the net commercial value of the dense forests in the region of the Blue Mountain ecoregion of eastern Oregon and southeastern Washington in the United States at \$650 per hectare. Same value was chosen here, rounded to €500 per hectare.

Agriculture

Some 20% of Corsican land is devoted to agriculture (191 104 hectares out of 872 200) according to [12]. However, a very large share can produce only fodder: in 2018, 165 180 hectares were permanent grassland, 7320 were artificial or temporary grassland, and 1400 where fallow-land. A large share of the 17 204 remaining hectares are devoted to chestnut, olive and clementine groves and vines. [12] provides data on the precise surface occupied by different types of agricultural products, the production by product, and the unitary price. These data are reproduced in Table 2 for the main products of Corsican agriculture. These data are used to estimate the value of the yearly production per hectare.

We assume that the value at risk corresponds only to the added value of the agricultural sector. [12] does not contain data about added value. Data found in [10] for the whole France in 2020 suggests that the added value for the agricultural sector corresponds to some 41% of the value of production. We use this rate to estimate the annual maximal loss.

However, as explained in detail in [17], burning some agricultural parcels such as vines or olive groves can have dynamic impacts. We assume that the annual damage has its maximal value the year where the fire took place, then shrinks at a yearly 20% rate, in order to account for the natural regeneration.

simulated in section 4.1.

Under these conditions, the value at risk would simply be the discounted value of a stream of income that would be required to compensate for the loss in added value. We choose a 5% rate for discounting. The value at risk is thus the estimated added value of one year of production divided by $.05 + .2$ (last column of Table 2).

Product	Prod. in 2018	Unit	Surface (ha)	Price per unit	Yearly value per ha	Dyn.	VAR per hectare
Olives (oil)	276	t	2150	€3500	€449	1	€736
Chestnut (flour)	15	t	1370	€15 000	€164	1	€269
Vines (wine)	374 649	hl	5884	€400	€25 469	1	€41 769
Clementines	37 336	t	1332	€2000	€56 060	1	€91 938
Fodder	403 993	t	285 370	€20	€28	0	€28

Table 2: Calculus for the cost per hectare for the main agricultural land-use. VAR: Value at risk

Buildings

The maximum value at risk in a building is the reconstruction cost. €1000 was chosen as the value per square meter, which might be slightly below the average construction cost for new buildings, in order to account for the older ones. In addition, a buffer is defined around the cells containing buildings, that replicates a share of the cost of these building, which is an admittedly quite ad-hoc way to account for all the inconveniences due to the proximity of a fire from inhabited areas. When a building is labeled "remarkable" in IGN data, it adds an arbitrary €50'000 to the value of the cell containing the building.

Human lives

Wildfires kill. Hopefully, only a minority of them do. Pricing the risk of fatalities is not an easy task in the context of this article. Indeed, most fatalities occur during exceptionally long events. In this work, assumes the fire can be stopped after a given duration, ranging from one hour to the simulated fire duration of eight hours. The probability to have a massive number of fatalities in less than eight hours is too low to account satisfactorily for those extreme cases. With that limitation in mind, estimation of human lives especially endangered in the case of wildfires are those of people in campsites or hiking paths. It is not taking account for the endangering of firefighters because this pertains to the intervention cost, whereas this paper only focuses on the proper cost of fires.

For campsites, the number of available beds is taken in all campsites (65 200)¹³ and assume they are evenly shared among the 204 registered campsites. This implicitly assumes that the campsites capacity is always full, which is not a re-

¹³source ATC, the Corsican Tourism Agency.

alistic assumption, since tourism in Corsica is a very seasonal activity. However, it is also true that most wildfires happen in the touristic season.

For hiking paths, it is assumed that 1000 hikers are permanently present over the 1563 kilometers of registered paths, which roughly corresponds to 0.2% of the population present on the island during the touristic season.

For both campsites and hiking paths is used a Value of Human Life (VHL) of €3 000 000 in order to give a price to the endangered lives. This value is within the wide range of values identified by [21] from \$1 million to \$10 millions.

Health

While health costs due to particle matters present in the smoke are an important part of the economics of wildfires, they were not taken into account in this paper. The reason is that in the case of small-medium scale fires that take place in a small density region like Corsica (less than 40 inhabitants per km²), health costs are likely to be marginal.

Estimating the catastrophic wildfires that took place in Florida in 1998, and that burnt some 200 000 hectares in 6 weeks, [6] estimate the health costs to be less than \$1 million, whereas the global cost is estimated between \$600 million and \$800 million. This would represent less than \$5 per burnt hectare. [20] estimate the health cost of the 2001 fire season in Chilsom, Alberta to be CAN\$4.1 × 10⁶ for 116 000 hectares burnt, which amounts to CAN\$35 per burnt hectare, a higher number than the one for Florida. Yet, this estimate relies on the assumption that more than 1 million people were exposed to smoke, which is unlikely to happen in the case of Corsica, where the whole population is less than 400 000, and spread along the coastal regions that are separated from each other by mountain chains.

Risk aversion

In the case of the 7 real fires (section 4.1), in addition to the average cost, we also compute a ‘Certainty Equivalent Cost’ (CEC), defined for a given fire i (in 1...7) at time t :

$$cec_{i,t} \equiv \sqrt{\frac{\sum_{j=1}^{500} c_{i,j,t}^2}{500}}$$

where $c_{i,j,t}$ is the simulated cost for fire i at time t in the j 's simulation.

This formulation simply gives more weight to the most severe outcomes, reflecting the fact that policy makers might be willing to pay an insurance prime in order to avoid bearing extreme costs. This calculus is purely illustrative and the choice of 2 as power of $c_{i,j,t}$ is arbitrary.

4. Evolution of the damage

4.1. Simulations of 7 real fires

Figure 5 presents the distribution of the final cost (after 8 hours) fire by fire. The simulations exhibit important variability, both within fire and between fires (mind the log scale). Figure 6 presents the CEC for the 7 fires, varying

from €90 630 in Chiatra to €16 344 510 in Calenzana. This variability comes both from the specifics of each fire and from the variability in meteorologic conditions. Analyzing the marginal impacts of duration requires that we remove these specific sources of variability. Thus, we estimate the marginal impacts of duration for the simulated fires using meteorological variables as regressors, with both fire and time fixed effects:

$$\Delta X_{i,j,t} = \alpha * W_{i,j,t} + \beta * M_{i,j,t} + \mu_i + \nu_t + \epsilon_{i,j,t} \quad (4)$$

Where $\Delta X_{i,j,t}$ is the marginal impact of fire $i \in [1; 7]$ calculated at simulation $j \in [1; 500]$ t minutes after ignition. $\Delta X_{i,j,t}$ denotes, respectively, the marginal cost, the marginal burned area, and the ratio between both, which is the cost per hectare of the marginal burned area.

The marginal cost of duration of a fire at a given time is simply calculated as the difference between the estimated cost at this time and the estimated cost one hour before. The same principle applies for the marginal burned area¹⁴.

$W_{i,j,t}$ and $M_{i,j,t}$ are the corresponding speed of wind and moisture. Wind and moisture are both expressed in standardized and mean-centered variables. μ_i and ν_t are fire and time fixed effects, and $\epsilon_{i,j,t}$ is an idiosyncratic shock.

Arguably the marginal cost of duration could have been estimated simply by averaging all the simulated marginal costs for a given duration. However, in the presence of changing meteorological conditions and of an important variability of costs between fires, the model 4 has the advantage to disentangle the impact of duration from other factors of the marginal cost. Notice that while the impact of wind and moisture are assumed linear, the use of time fixed-effects does not imply a linear relationship between the marginal cost and time.

The results of this regression for the marginal cost of duration are presented in Table 3, that shows the predictable impact of wind (positive) and moisture (negative).

Figure 7 presents the evolution of the estimated marginal cost over time. These estimates are obtained by adding the time fixed effect to a virtual overall intercept computed using the function *within_intercept* of the plm package in R. The estimates does not include the speed of wind and the moisture, which means that they are based on average values for both variables (because both are included in the regressions as mean-centered variables). A 95% confidence interval is displayed around the estimates. The black line represents the regression based on all the simulations.

This figure exhibits a surge in the marginal cost of duration after 300 minutes. The marginal cost remains in the €150 000 to €330 000 range before 300 minutes, and then surges from €430 000 to stabilize around €600 000 after 380 minutes. Equation (4) assumes that the impact of meteorological conditions on the marginal cost of duration is constant. In order to allow for a more complex

¹⁴The choice has been made to differentiate over a 1 hour time-length (3 20-minute time steps of the simulations) because it seems more telling to speak in terms of one hour than in terms of twenty minutes. This choice is quite arbitrary, though.

impact, we run a similar regression on a subset of the data defined by the 50% windiest simulations for each of the 7 fires¹⁵. The normalized moisture and speed of wind are recalculated based on the means and standard deviations at the subset level. The red line of figure 7 the evolution of the marginal cost for this subset of simulations. In this case, the surge at 300 minutes is even sharper, and the marginal cost stabilizes between €900 000 and €1 000 000 after 380 minutes.

Table 4 and Figure 8 present the same exercise for the cost per hectare of the marginal burned area, whereas Table 5 and Figure 9 present the same exercise for the marginal burned area. As for the global cost, wind and moisture have a significant impact on both the cost per hectare and on the marginal burnt area. Clearly, the significant impact of meteorological conditions on the cost per hectare is human-made phenomenon. It is due to the seven fires having their ignition points away from the most valuable places. It might be because the less valuable places are less watched by firefighters. As a consequence, when the fires evolve quickly, they tend to burn lands with higher values than the lands close to the ignition point. This finding strengthens the view that taking real-life ignition points is more relevant than just randomly drawing them.

Overall, these results confirm our expectations that the marginal cost of duration increases over time through both a human mechanism and a physical mechanism.

4.2. Simulations over the Whole Corsica

The simulations performed in subsection 4.1 rely on precise data about ignition points and times. But generalizing the results obtained through the study of only 7 fires would certainly be unwise. In this subsection, we present the results of similar simulations for 933 real but very approximate ignition points¹⁶, that we simulate for 14 real extreme meteorological conditions observed in Corsica between 2017 and 2019, for which we collected precise data. The results are presented in tables 6 (for the marginal cost), 7 (for the cost per hectare of the marginal burnt area) and 8 (for the marginal burnt area).

Figures 10, 11 and 12 present the evolution of the three variables over time, using the same methodology as the one described in section 4.1

The shape of Figure 10 is pretty close to the shape of Figure 7, confirming the sharp increase in the marginal cost of duration over time. The order of magnitude is closer to the one of the 50% events (*ie* the red line of Figure 7). This is due to the 14 meteorological conditions being chosen as extreme conditions, favorable to a rapid increase in the burnt surface. However, in this case, the increase in the marginal cost is entirely due to the increase in the marginal burnt area, displayed in figure 12. The cost per hectare of the

¹⁵More precisely, we assign to each of the 500 simulations a speed of wind that corresponds to the highest wind speed within the 24 time steps of the simulation.

¹⁶Prométhée database provides the coordinates of the polygon within which the fire started in the DFCI system, and we take the centroid of this polygon as our ignition point.

marginal burnt area, on the other hand, is roughly constant, as can be seen in Figure 11. While this result contradicts the *human mechanism* highlighted in the previous subsection, it would be very unlikely to observe such a phenomenon at this scale. Indeed, in DFCI coordinate system, a $2km \times 2km$ square is divided into 5 polygons as displayed in Figure 4, which corresponds, on average, to 80 hectare per polygon. Thus, the likelihood that the actual ignition point is close to the centroid is quite low.

Notice that, given the extreme meteorological conditions included in the simulations, the estimates of the marginal cost of duration are of a higher order of magnitude than the ones found in 4.1. However, again, it is the time-evolution of the cost that is of first interest, while the level is more secondary, since it strongly depends on the scaling parameter.

To sum up, this second set of simulations:

- Confirms the sharp increase in the marginal cost of duration.
- Confirms the role of the physical mechanism in this increase.
- Does not confirm the role of the human mechanism, but could not confirm it whatsoever, because of the imprecise data on ignition points.

Independent variable	coefficient	SE	P-value
Overall Intercept (1)	71 937.7	29 741.1	$< 0.016^*$
moisture	-158 640.2	7941	$< 2.2e^{-16} * **$
speed of wind	502 648.1	9389	$< 2.2e^{-16} * **$
Number of observations	73 500		
F	196.3		$< 2e^{-16} * **$

Table 3: Dependent variable: 1-hour difference of the cost of the fire. 7 fire case. The 73 500 observations correspond to 7 fires times 500 simulations times 21 20-minute time steps. Fire and time fixed-effects are not reported in this table. (1) the Overall intercept is computed using *within_intercept* of the plm package in R.

Independent variable	coefficient	SE	P-value
Intercept	289.1	66.7	$1.5e^{-5} * **$
moisture	-118.6	17.8	$2.8e^{-11} * **$
speed of wind	365.8	21.1	$< 2.2e^{-16} * **$
Number of observations	73 500		
F	25.9		$< 2.2e^{-16} * **$

Table 4: Dependent variable: cost per hectare for the marginal hour. 7 fire case. The 73 500 observations correspond to 7 fires times 500 simulations times 21 20-minute time steps. Fire and time fixed-effects are not reported in this table. (1) the Overall intercept is computed using *within_intercept* of the plm package in R.

Independent variable	coefficient	SE	P-value
Intercept	104.5	6.2	$< 2.2e^{-16}$ * **
moisture	-124.8	1.7	$< 2.2e^{-16}$ * **
speed of wind	245.0	2.0	$< 2.2e^{-16}$ * **
Number of observations	73 500		
F	1363		$< 2.2e^{-16}$ * **

Table 5: Dependent variable: 1-hour difference of the surface of burnt area. 7 fire case. The 73 500 observations correspond to 7 fires times 500 simulations times 21 20-minute time steps. Fire and time fixed-effects are not reported in this table. (1) the Overall intercept is computed using *within_intercept* of the plm package in R.

Independent variable	coefficient	SE	P-value
Overall Intercept (1)	94 698.7	19 939	$< 2.04e^{-06}$ * **
moisture	-326 559.9	4550	$< 2.2e^{-16}$ * **
speed of wind	508 179.2	4371.8	$< 2.2e^{-16}$ * **
Number of observations	274 302		
F	970.2		$< 2e^{-16}$ * **

Table 6: Dependent variable: 1-hour difference of the cost of the fire. Whole Corsica. The 274 302 observations correspond to 933 ignition points times 14 meteorological conditions times 21 20-minute time steps. Fire and time fixed-effects are not reported in this table. (1) the Overall intercept is computed using *within_intercept* of the plm package in R.

5. Discussion

The results presented in the previous section rely on a model where firefighting actions are totally absent. Thus, they should not be considered as a realistic estimate of the actual costs of the fires but more of what-if simulated scenari. For instance, the endangerment of human life is probably overestimated, because in real life situations, firefighters generally prioritize saving human lives over other immediate objectives. However, those simulations can make sense since they pinpoint the hot-spots that are the worthiest saving. In other words, the costs presented here should be interpreted as the maximum cost of a worthwhile intervention aiming at stopping a fire. Anyway, it is hoped that the coupled fire-economy model can help firefighters sizing their interventions and directing them toward the most sensitive areas or to the least use the 5 hours threshold to take fire fighting planning decisions. Corsica is also very typical of a Mediterranean climate and landscape that may be found in parts of Australia, California, and Europe, so this model may be adapted to other regions as an operational tool for firefighting management.

Beside these practical matters, it was not expected to find how large the gross gain from rapid intervention seems to be. Needless to say, a complete economic analysis of wildfire duration would require a careful account for the firefighting cost, with its complex balance between fixed cost and variable cost, fuel management policy, suppression and prevention. Again, that would go beyond the scope of the present paper. But as a of discussion, by roughly

Independent variable	coefficient	SE	P-value
Intercept	2800.5	124.2	$2.2e^{-16}$ * **
moisture	-32.6	28.4	0.250
speed of wind	286.9	27.2	$< 2.2e^{-16}$ * **
Number of observations	274 302		
F	9.9		$< 2.2e^{-16}$ * **

Table 7: Dependent variable: cost per hectare for the marginal hour. Whole Corsica. The 274 302 observations correspond to 933 ignition points times 14 meteorological conditions times 21 20-minute time steps. Fire and time fixed-effects are not reported in this table. (1) the Overall intercept is computed using *within_intercept* of the plm package in R.

Independent variable	coefficient	SE	P-value
Intercept	66.78	3.9	$< 2.2e^{-16}$ * **
moisture	-205.4	0.9	$< 2.2e^{-16}$ * **
speed of wind	282.3	0.8	$< 2.2e^{-16}$ * **
Number of observations	274 302		
F	8802.3		$< 2.2e^{-16}$ * **

Table 8: Dependent variable: 1-hour difference of the surface of burnt area. Whole Corsica. The 274 302 observations correspond to 933 ignition points times 14 meteorological conditions times 21 20-minute time steps. Fire and time fixed-effects are not reported in this table. (1) the Overall intercept is computed using *within_intercept* of the plm package in R.

estimating a reduction of the duration of a given fire by one hour would require 3 hours of use of 5 water-bomber aircraft, which sounds like a comfortable support. If one hour of aircraft costs €10 000, then this extra support would be barely worthwhile in the case of slow-wind events. In fact, in these situations, aircraft might not even be necessary to achieve rapid containment of the fire. In the presence of wind, on the other hand, such massive support would more than pay for itself, at least from a social point of view, even before the break at 5 hours. And even if these estimates strongly depend on the choice of a scaling parameter, the mean cost per hectare falls in the range of cost estimates found in the literature. Moreover, the difference between the roughly €500 000 marginal cost of duration and the €150 000 of this hypothetical support is so massive that it would probably resist a quite substantial fall in the scaling parameter. To be clear, saying that a massive intervention would pay for itself does not mean it would be an optimal policy: other actions such as prioritizing the protection of the most sensitive parcels might be a less costly way to mitigate the cost of a fire. But a €500 000 to €1 × 10⁶ marginal cost for the windiest events leaves a lot of room for even costly interventions to be worthwhile.

6. Conclusion

Wildfires are obviously not a *normal* phenomenon whose upper tail can be neglected. But even the central part of the distribution is worth studying. The

simulations we performed in this article suggests that reducing the duration of small scale fires could well pay for itself. A wildfire simulator was used to run two sets of virtual 8-hour long events. For the first set, the ignition points and meteorological conditions were chosen from 7 real fires that took place in Corsica between 2017 and 2018. The second set mixes 933 approximate starting points of real events that occurred in Corsica with 13 extreme meteorological conditions. Assessing the cost of real-life wildfires requires a very careful investigation to observe the extent to which the burnt areas are impacted. There is no known equivalent of such investigations in the case of simulated fires, with results may be taken with caution, but parameterization of the simulations were made so as to generate a mean cost per hectare (€638) that is in line with values that are reported in the literature. Our different scenarios suggest that the marginal cost tends to rise to reach between €600 000 and €1 000 000 after 6 hours. This finding is an argument for trying to reduce the duration of already small fires, even if this assertion should be supported by a careful analysis of the fighting cost side of the equation that is not provide here.

We hope that the integrated tool presented in this article will contribute to feed the fire-fighting policy making, in line with the 10th recommendation of French Senator Vogel's report on the bush fire policy[26]: "in order to improve knowledge of the costs of damages related to forest fires, initiate work on the development of an assessment tool economic loss and damage caused or likely to be caused."

Eventually, this tool aims at finding other purposes than just estimating the marginal cost of fire duration. These other purposes include the real-time crisis management and long term planning, in terms of fuel and urban-wild interface management.

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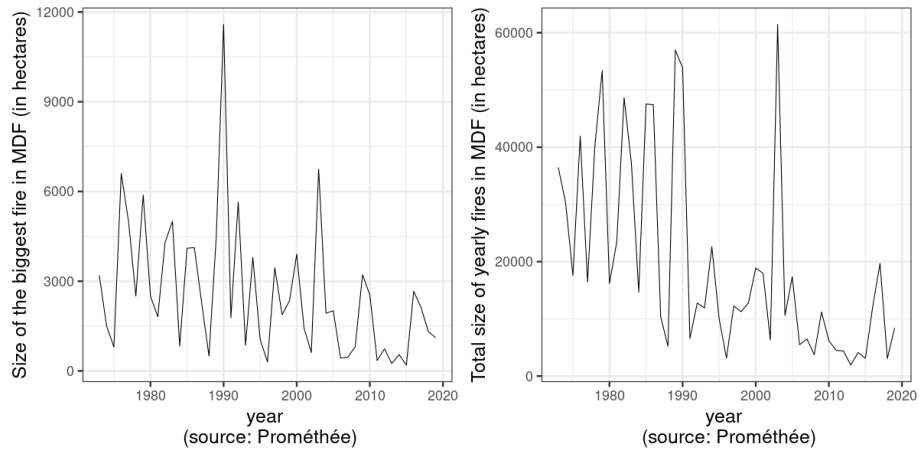


Figure 1: Size of the largest versus total size of wildfires in France between 1973 and 2019

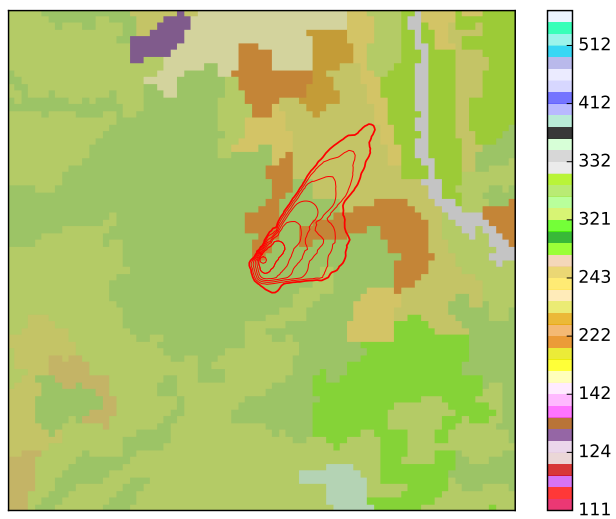


Figure 2: Representation of simulated fire spread. The red contours are isochrones of a simulated fire front separated by ten minutes of spread, for a total duration of one hour. The fire started at the center of the figure. Background colors correspond to a land use raster at 80-m resolution derived from Corine Land Cover [7] data. The Nomenclature of Corine Land Cover can be found at <https://www.eea.europa.eu/publications/COR0-part2> (the colors and numbers of the legend correspond to this nomenclature).

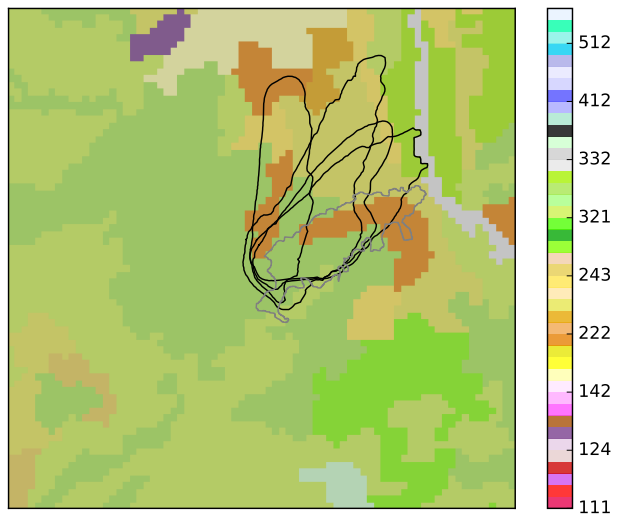


Figure 3: Ensemble of wildland fire simulations. The black contours indicate some of the simulated fire fronts after 1h of propagation. The gray contour delineates the burned surface observed at the end of the actual wildfire. Background colors correspond to a land use raster at 80-m resolution derived from Corine Land Cover [7] data. The Nomenclature of Corine Land Cover can be found at <https://www.eea.europa.eu/publications/COR0-part2> (the colors and numbers of the legend correspond to this nomenclature).

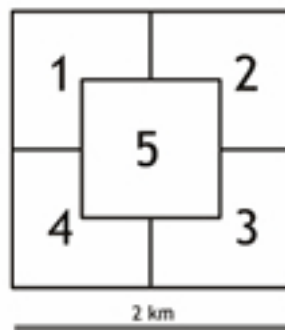


Figure 4: DFCI coordinate system. Source: IGN

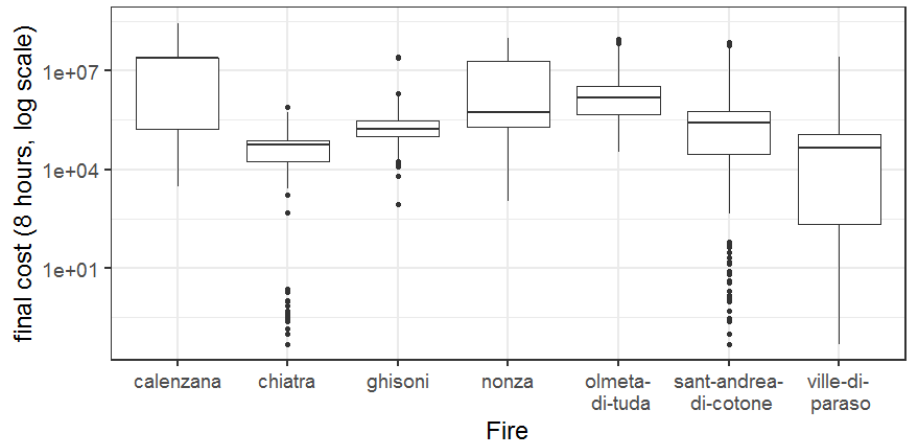


Figure 5: The distribution of the cost after 480 minutes for the 7 fires

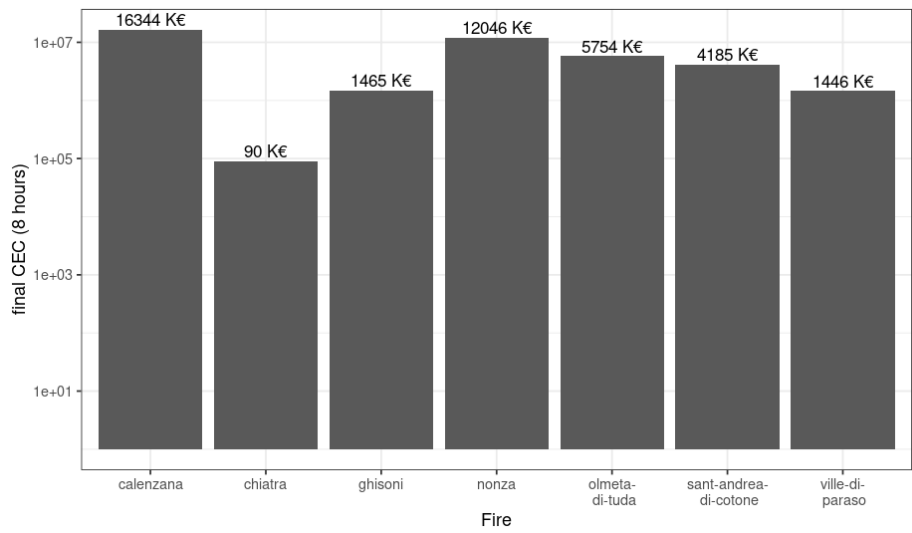


Figure 6: CEC after 480 minutes for the 7 fires

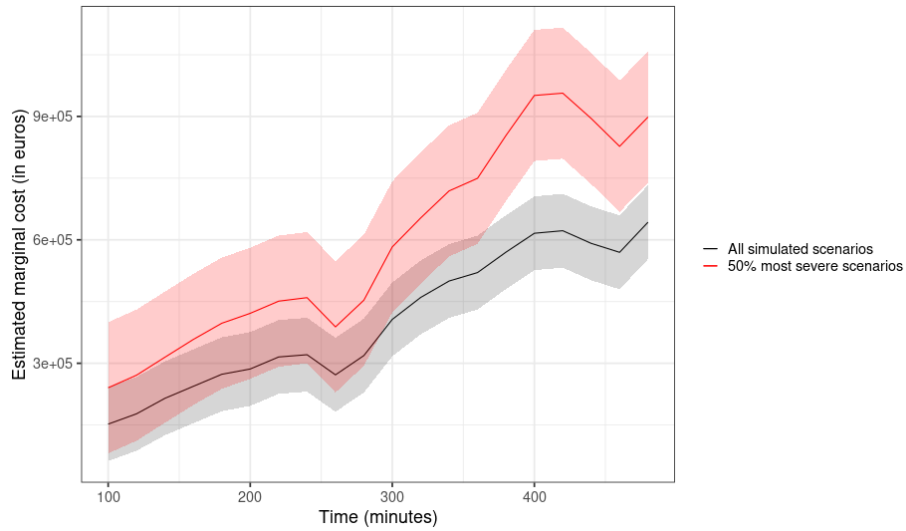


Figure 7: Estimation of the marginal cost of duration (for average speed of wind and moisture) - 7 fires. The estimates are obtained by adding the time fixed effect to a virtual overall intercept computed using the function *within_intercept* of the plm package in R. The estimates does not include the speed of wind and the moisture, which means that they are based on average values for both variables. The shaded areas represent a 95% confidence interval around the estimates.

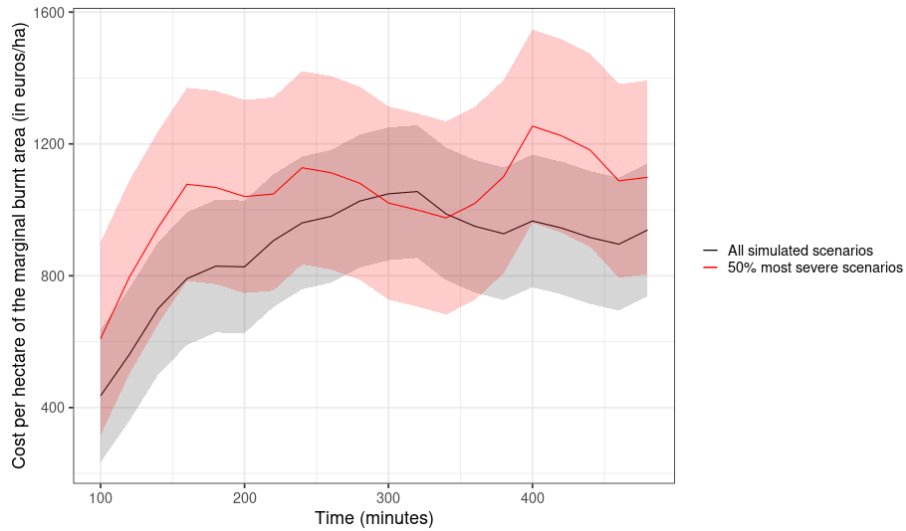


Figure 8: Estimation of the cost per hectare for the marginal burnt area (for average speed of wind and moisture) - 7 fires. The estimates are obtained by adding the time fixed effect to a virtual overall intercept computed using the function *within_intercept* of the plm package in R. The estimates does not include the speed of wind and the moisture, which means that they are based on average values for both variables. The shaded areas represent a 95% confidence interval around the estimates.

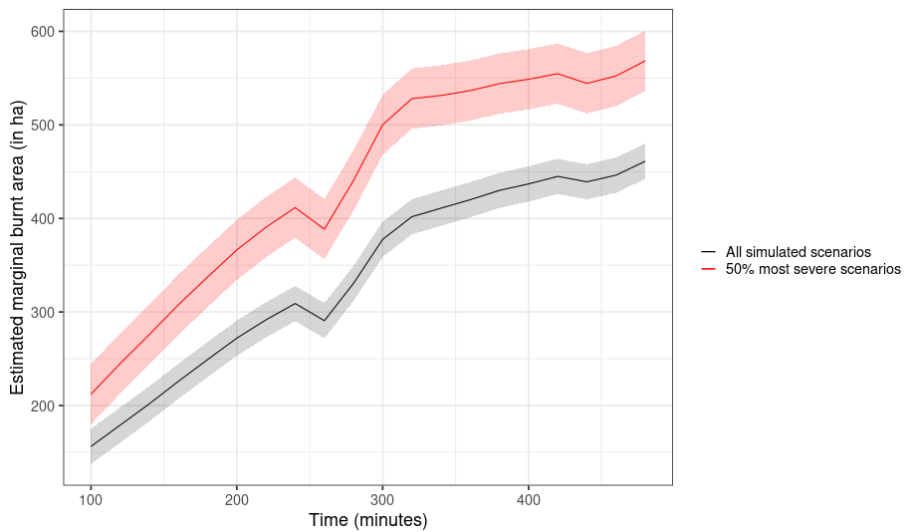


Figure 9: Estimation of the marginal burned area (for average speed of wind and moisture)- 7 fires. The estimates are obtained by adding the time fixed effect to a virtual overall intercept computed using the function *within_intercept* of the plm package in R. The estimates does not include the speed of wind and the moisture, which means that they are based on average values for both variables. The shaded areas represent a 95% confidence interval around the estimates.

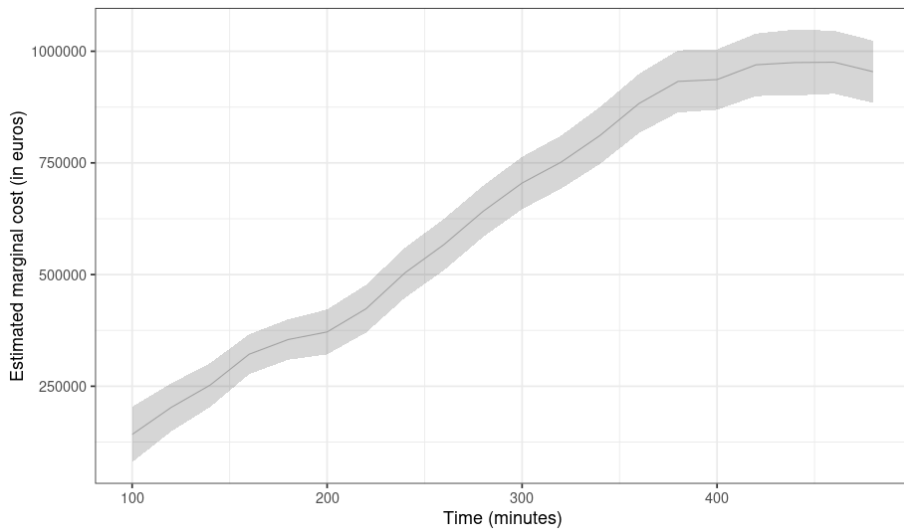


Figure 10: Estimation of the marginal cost of duration (for average speed of wind and moisture) - Whole Corsica. The estimates are obtained by adding the time fixed effect to a virtual overall intercept computed using the function *within_intercept* of the plm package in R. The estimates does not include the speed of wind and the moisture, which means that they are based on average values for both variables. The shaded area represents a 95% confidence interval around the estimates.

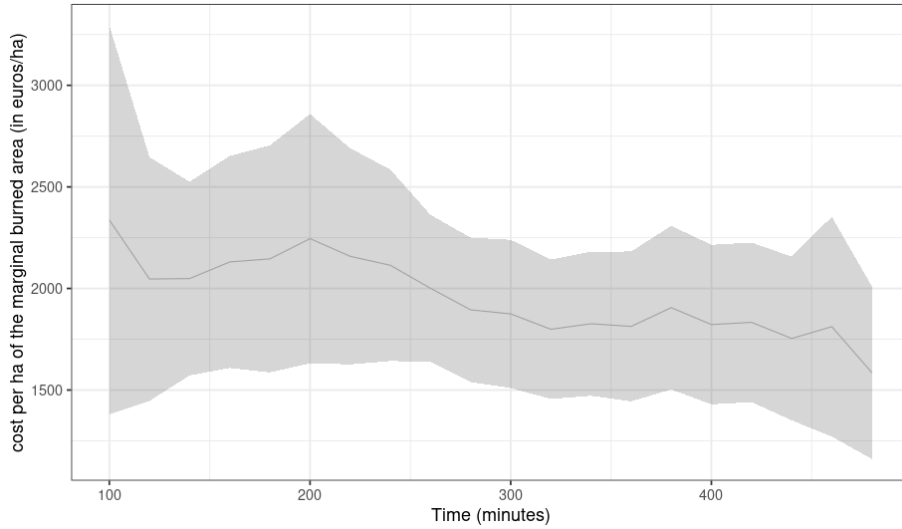


Figure 11: Estimation of the cost per hectare for the marginal burnt area (for average speed of wind and moisture) - Whole Corsica. The estimates are obtained by adding the time fixed effect to a virtual overall intercept computed using the function *within_intercept* of the plm package in R. The estimates does not include the speed of wind and the moisture, which means that they are based on average values for both variables. The shaded area represents a 95% confidence interval around the estimates.

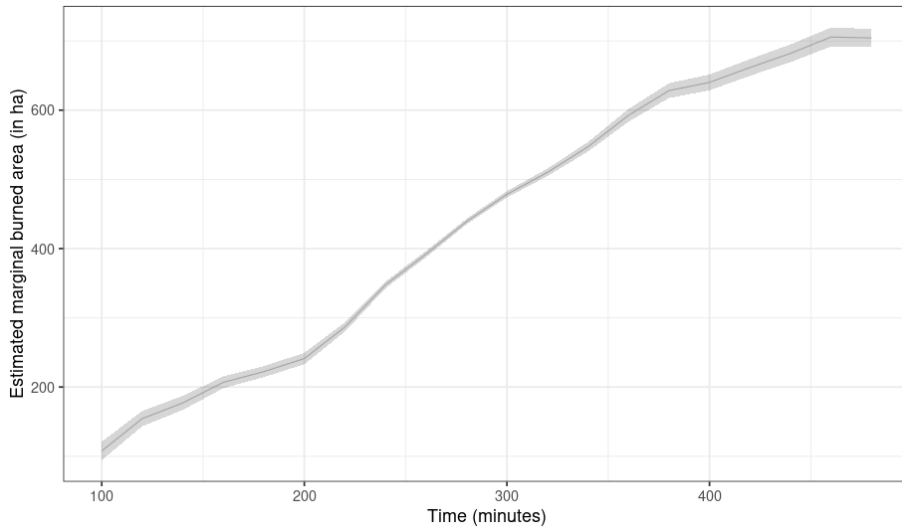


Figure 12: Estimation of the marginal burned area (for average speed of wind and moisture) - Whole Corsica. The estimates are obtained by adding the time fixed effect to a virtual overall intercept computed using the function *within_intercept* of the plm package in R. The estimates does not include the speed of wind and the moisture, which means that they are based on average values for both variables. The shaded area represents a 95% confidence interval around the estimates.