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Potential Effects of Climate Change on Fire Behavior, Economic Susceptibility and Suppression Costs in Mediterranean Ecosystems: Córdoba Province, Spain

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Abstract: The potentially large ecological, economic, and societal impacts of climate change makes it a significant problem of the 21st century. These consequences have led to tremendous development in climate change scenarios and new technologies to increase knowledge on the effect and efficiency of mitigation and adaptation measures. Large fires will occur at a higher rate than currently because of lower fuel moisture content resulting in a lower resistance to burning. This is also evidenced by more extreme fire behavior that contributes to higher economic impacts, suppression difficulties and suppression costs. The economic susceptibility concept integrates a set of economic valuation approaches for valuing timber and non-timber resources, considering the fire behavior, and as a consequence, the net value changes for each resource. Flame length increased by 4.6% to 15.69%, according to the different future climate scenarios. Climate change is expected to cause widespread changes to economic susceptibility and suppression costs because of higher flame length and fire intensity. Therefore, our outcomes show an increase in the economic susceptibility of Córdoba Province in the medium and long term (2041–2070) between 6.05% and 25.99%, respectively. In addition, we have found an increase between 65.67% and 86.73% in suppression costs in the last decade. The digital version of the economic susceptibility model using Geographic Information Systems improves its operational capabilities enhancing also its dynamism and simplicity to accept modifications and predictions revisions.

Keywords: fire management; fire susceptibility; net value change; fire intensity level; aerial and terrestrial firefighting resources

1. Introduction

Nowadays, wildfires have become one of the most significant disturbances worldwide [1–6]. The combination of a longer drought period and a higher woody biomass and flammability of dominant species creates an environment conducive to fire spread [7,8]. Furthermore, vegetation pattern changes with the abandonment of traditional rural activities plays a direct role in the increase of fire severity and ecological and economic fire impacts [1,9]. Fire behavior exceeds most frequently firefighting capabilities and fire agencies experience difficulties in suppressing flames while providing safety for both firefighters and citizens [10].

Climate change would have an essential influence on fire regime and ecosystem dynamics [3]. Therefore, long-term projections were carried out using general circulation models (GCMs) [11]. However, projections of extreme events, such as droughts and heatwaves, must be analyzed from studies at regional o local scales [11–13]. GCMs involve statistical "downscaling" or an empirical relationship between the general circulation variables and local variables, such as convection process and topography [13,14]. All CGMs results would fluctuate depending on the assumptions of one or another Special Report on Emission scenarios (SREs) based on the economic and technological development and demographic change (A1, A2 and B1 scenarios) [15]. These SREs were superseded by Representative Concentration Pathway scenarios (RCPs) [16]. The four RCPs scenarios, namely RCP2.6, RCP4.5, RCP6 and RCP8.5 were labeled after a possible range of radioactive forcing values in the year 2100 [16].

The last decade in the northern hemisphere has been the hottest since meteorological records began [16]. A temperature increase entails a greater risk of large fires because of the lower fuel moisture content (FMC) and the greater fuel availability [17]. All GCMs show increases in future temperatures, mainly in summer temperatures [18]. Temperature increases to a greater or lesser degree are based on the selected SREs or RCPs. According to the temperature differences, both scenarios can be used to estimate the decrease on FMC. Therefore, a change in fire intensity and severity [1,19], the frequency of large fires [4,20] and the annual area burned [1,19–22] can be assumed. This expected fire regime change would lead to higher economic impacts [6,23–25] and to larger fire suppression difficulties [10,26], and as a consequence, to higher suppression costs [27–29]. The increase of suppression difficulties entails the incorporation of a greater number of firefighting resources in order to mitigate fire-line spread. The suppression difficulties index has a strong relation with the energy release from the fire [26]. In this sense, we can affirm that the fire virulence and the suppression difficulty conditions will increase under the different climate change scenarios, and as a consequence, also suppression costs.

The aim of this study was to identify economic fire susceptibility of tangible assets and suppression costs under projected climate change (period 2041–2070). A general increase in temperatures and decrease in relative humidity was estimated using a downscaling technique. Given the uncertainty of anthropogenic influences, three future scenarios were proposed based on the modified fuel moisture content and fire behavior over the surface and canopy fuels. Fire behavior was modified unevenly under three future scenarios, increasing the economic impacts and suppression costs of forest fires. Therefore, fire susceptibility under the three future scenarios was estimated integrating tangible assets valuation and potential fire behavior, and as a consequence, net value change of the forest resources [30]. Finally, we included a comparative analysis of suppression costs in the study area between different periods. Knowledge of future changes in economic susceptibility and suppression costs is needed for constructing adaptation strategies and for developing efficient fire suppression resources allocation for fire prevention and mitigation activities.

2. Materials and Methods

2.1. Study Area

The study area is Córdoba province, located in southern Spain, with an area of 1,376,150 hectares (Figure 1). The Mediterranean climate is conducive to ignition and propagation of forest fires because of its high summer temperature reaching upwards of 40 °C. This elevated temperature together with a low relative humidity and a very low annual precipitation cause low fuels' moisture heightening fire ignition risk. In addition to these ignition conditions, wind velocity increases the initial spread of fire, and as consequence, its burned area. For the period of 1990–2018, the fire statistics of Córdoba province show a mean annual number of 114 fires and a mean burned area of 573.22 ha. Over 90% of the Cordoba province's wildfires are anthropogenic in nature (Forest Department, personal communication). Although our study does not evaluate the increase in fire ignition resulting from the lower fuel humidity, some authors associate the increase in fuel availability with an increase in wildfires [31].

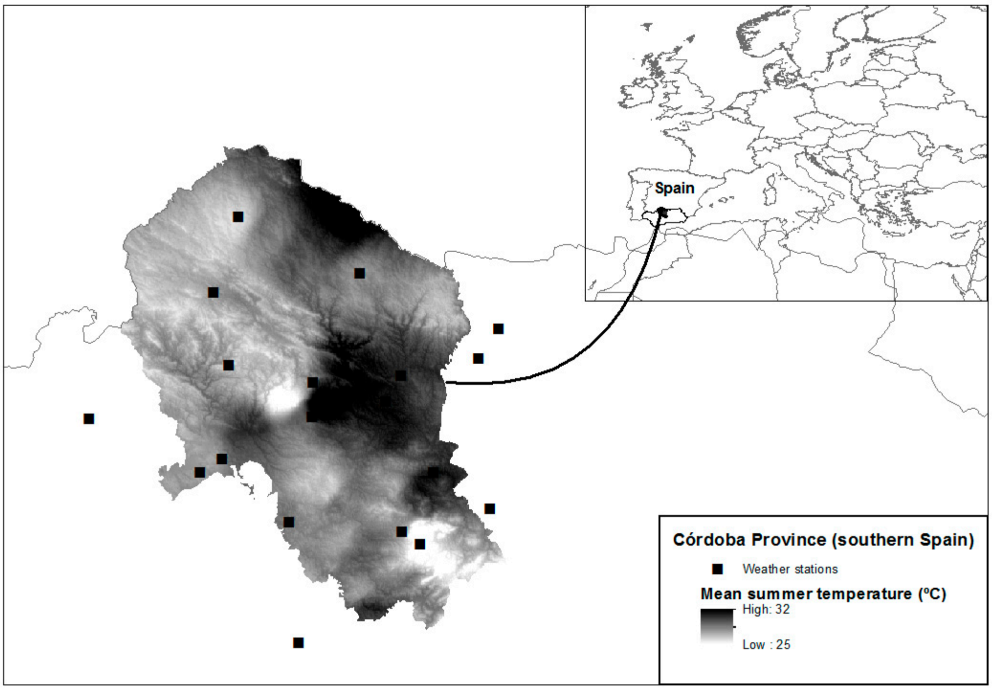

Figure 1. Study area location with selected weather stations.

The central part of the province has a gentle topography becoming rugged as we moved southerly or northerly making fire suppression conditions more difficult. Over 80% of the tree cover is dominated by *Quercus ilex*, in association with *Pinus* plantations, mainly with *P. pinea* and *P. pinaster*. Shrubs are dominated by *Cistus* spp., in association with *Quercus coccifera*, *Pistacia lentiscus*, *Phyllirea angustifolia*, *Arbutus unedo*, *Olea europaea* var. *sylvestris*, *Rosmarinus officinalis*, *Pistacia terebinthus*, *Retama shaerocarpa*, *Teucrium fruticam Thymus mastichina* and *Lavandula stoechas*.

2.2. Climate Scenarios Development

There are different standardized GCMs such as the Third Generation Coupled Global Climate Model (CGCM3) and the European Center model with Hamburg physics (ECHAM5) [16]. For this study, the length of the projections was to extend only to 2070, a time horizon for which the concentration scenario uncertainty is less relevant. We used linear and non-linear methods (statistical downscaling analysis) to establish linear relationships between predictor(s) and predicted [32]. Key inputs include summer data (1961–2000) for both temperature and relative humidity as well as GCM outputs for large-scale variables for future climate. The current period (2001–2018) provides climate information at the study area (weather stations) for which there is appropriate datasets to identify the most interesting GCM output and the best downscaling method. Because of this, we used CGCM3, which produces the most unfavorable temperature for the considered period (2041–2070).

There was a great heterogeneity in the spatial information of the 19 weather stations used, so even very close stations showed significant differences. Then, different statistical downscaling methods can generate different scenarios even when formed with the CGCM3. We evaluated 17 downscaling techniques (Table 1) to extrapolate the weather information to Córdoba province. When using geostatistical extrapolation techniques we used different topographic datasets like altitude, slope and slope-aspect; climate datasets like wind speed and direction; and geographic datasets like forest area (forest and treeless lands), canopy cover (%) and delimitation of watersheds and valleys bottoms. We used 74% of the weather stations to extrapolate temperature and relative humidity (average values in summer period) according to the different downscaling techniques. Finally, we used the remaining 26% of weather stations to test the best predictions based on the mean absolute error.

Table 1. Statistical downscaling techniques applied for the study area.

Downscaling Technique	Variables	Reference
Global Polynomial Interpolation	Temperature, relative humidity	[33]
Inverse Distance Weighting	Temperature, relative humidity	[33–35]
Local Polynomial Interpolation	Temperature, relative humidity	[33]
Radial Basis Functions	Temperature, relative humidity	[33]
Kriging	Temperature, relative humidity	[33–35]
Cokriging	Temperature, relative humidity, altitude	[33–35]
Cokriging	Temperature, relative humidity, altitude, aspect	[33–35]
Cokriging	Temperature, relative humidity, altitude, slope	[33–35]
Cokriging	Temperature, relative humidity, slope, aspect	[33–35]
Cokriging	Temperature, relative humidity, altitude, slope, aspect	[33–35]
Cokriging	Temperature, relative humidity, altitude, slope, wind speed	[33–35]
Cokriging	Temperature, relative humidity, altitude, slope, canopy cover	[33–35]
Cokriging	Temperature, relative humidity, altitude, slope, forest area	[33–35]
Cokriging	Temperature, relative humidity, altitude, aspect, forest area	[33–35]
Cokriging	Temperature, relative humidity, altitude, slope, wind speed	[33–35]
Cokriging	Temperature, relative humidity, altitude, slope, valley bottom	[33–35]
Cokriging	Temperature, relative humidity, altitude, slope, watersheds	[33–35]

The absence of future scenarios for fuel moisture and its variability according to each SRE (A1, A2 and B1) and RCP (RCP2.6, RCP4.5, RCP6 and RCP8.5) [36] lead us to identify different scenarios for fuel moisture based on temperature and relative humidity. We proposed three future scenarios for FMC (Table 2) considering different changes in temperature and relative humidity according to each SRE or RCP: an unfavorable scenario (S1), an intermediate scenario (S2) and a favorable scenario (S3). The maximum difference between each SRE and its associated RCP for the study area was 0.4 °C (Table 2) resulting in a fuel moisture decrease between 0.1% and 1%. According to these minor meteorological changes, flame length and suppression costs differences between each SRE and its associated RCP would be minimal.

Table 2. New fuel moisture content (FMC) scenarios created based on Special Report on Emission (SRE) and Representative Concentration Pathway (RCP) scenarios.

FMC Scenario	SRE Scenario	Temperature Increase (°C)	Relative Humidity Decrease (%)	RCP Scenario	Temperature Increase (°C)	Relative Humidity Decrease (%)
S1	A1	1.8–2.2	6.4–9.6	RCP 8.5	1.8–2.6	6.4–11.3
S2	B2	1.3–1.5	3.3–5.5	RCP 6.0	0.8–1.8	2.1–6.1
S3	B1	0.4–0.8	1.8–2.8	RCP 2.6	0.5–1.2	2.2–4.2

Using destructive sampling (unpublished dataset and Supplementary Material 1) we identified a wide range of summer records from permanent plots related to fine dead fuel moisture content (FFMC) and live fuel moisture content (LFMC) for the period 2005–2018. Fuel samples were taken during the summer months in Córdoba and oven dried at 70 °C for 72 h [37]. A multiple linear regression was used to develop a model for predicting FFMC from different weather conditions. FFMC was extrapolated to the study area for S1, S2 and S3 based on the most reliable deterministic and geostatistical technique. LFMC depended on the species, the annual weather conditions (temperature, relative humidity and annual precipitation), the slope-aspect and the fuel shading [26]. In a similar way to FFMC, LFMC was directly related to temperature and indirectly related to relative humidity under the same vegetation and similar topographical conditions. Because our objective is not to study in depth the moisture content of live fuels, average LFMC for S1, S2 and S3 was estimated from historical records of the relationship between LFMC, temperature and relative humidity according to the vegetation composition. Dominant species (Supplementary Material 1) in each fuel model or ecosystem and slope and aspect were considered in the estimation of live fuel moisture using a Geographic Information System (GIS).

2.3. Fire Behavior

Fire behavior is a complex phenomenon resulting from the association of meteorological, topographic and vegetation variables [38,39]. Even though socioeconomic changes in land uses and the abandonment of agricultural activities and cattle ranching could cause changes in vegetation combustibility [40], these were not considered. Therefore, vegetation structures (fuel load and species composition) are not significantly influenced by climate change.

In this approach, the impact of FMC decrease on fire behavior is a progressive desiccation of the vegetation and a lower resistance to burn given a heat source. Moreover, the combustion velocity increases (the released water vapor is absorbed faster) as the air is desiccated facilitating fire spread. Therefore, a lower FMC is related to a higher spread rate, flame length and fire intensity. Fire spread simulators such as Farsite©, FlamMap©, Visual Fuego© [39,40] and Visual SEVEIF [41] could be used to estimate the future fire behavior under the three scenarios conditions (S1, S2, S3).

2.4. Economic Susceptibility from Forest Fires

Although the economic valuation should include market and non-market resources [6,23], this study only takes into account tangible assets (both timber and non-timber resources) and carbon storage resource. Tangible assets are measured based on field inventories, historical records or substitute markets. Timber resource impacts were valued using the techniques of the National Fire Management Analysis System (United States Department of Agriculture (USDA) Forest Service) as adapted to the Mediterranean Basin conditions [23] (Table 3). Non-timber losses (acorn or other fruit production and cork production) were valued according to the mean annual production, the estimated resource price and the number of years between the time of the fire and the rotation age or senescence [42] (Table 3). Pasture loss was calculated using the annual income given the site'scarrying capacity, the need of livestock demarcation and the hay price (substitutive market until recovery) [42]. Hunting resource was valued in terms of its sustainable hunting profit, reproductive stock and vegetation resilience [43] (Table 3). Finally, carbon storage losses can be valued like any other tangible assets [25] (Table 3) because they can be traded on the international credit markets (www.sendeco2.com).

Table 3. Formulations used for economic valuation.

Resource	Formula	Potential Status	Source
Timber	$L = (a*S*N)/(S + b*N)$	Immature and mature stands	[23]
	$S = C_0*t\,[r^e + i(r^e - 1)] + F*(r^e - 1)$	Immature stands	
	$N = [(P*V*1.025^y)/1.04^y] * [1 - (1.025/1.04)^e] * [1 + M*c*t]$	Immature stands	
	$S = [P*V - P_1*V_1] + P*V\,[(r^{(R\text{-}e)} - 1)/(r^{(R-e)})]$	Mature stands	
	$N = V*c*t\,[C*P + (1 - C)*P_1]$	Mature stands	
Firewood; fruit production	$L = A_p*P_r*\,[((1 + r)^y - 1)/(r*(1 + r)^y]$	Mature stands	[42]
Pasture production	$L = V*\,[((1 + 0.06)^n - 1)/(0.06*(1 + 0.06)^n]$	Livestock area	[42]
Hunting activity	$L = V*\,[((1 + 0.06)^n - 1)/(0.06*(1 + 0.06)^n] + S_t$	Game area	[43]
Carbon storage	$L = 3.67*CS*P_c + AS\,[((1 + r)^{(R\text{-}e)} - 1)/(r*(1 + r)^{(R-e)}]$	Woodlands	[25]

where "L" is the resource loss (€/ha), "S" is the valuation according the Spanish system (€/ha), "N" is the valuation adapted from NFMAS (National Fire Management Analysis System, €/ha), "a" takes the value of 1.7 or 2.6 according to protection or recreational function, or timber forest respectively, "b" takes the value of 0.85 or 0.25 base on the same reasons, "C_0" is the reforestation cost per hectare (€/ha), "t" is the percentage burned stand based on fire behavior, "r" is the compound annual interest rate and depends on species growth rate: fast growth (1.06), medium growth (1.04), slow growth (1.025) and very slow growth (1.015) [20]; "e" is the estimated stand age, "i" is the annual silvicultural cost factor and depends on species growth rate: fast growth (1.27), medium growth (1.1) slow growth (1.1) and very slow growth (0.93), "P" is the price of the timber (€/m^3), "V" is the timber volume (m^3/ha), "y" is the time or years remaining in the harvesting rotation or senescence age, "M" is the tree mortality coefficient depending on fire intensity, "c" is the percentage of immature or mature timber in stand, "P_1" is the price of affected timber with commercial use (€/m^3), "V_1" is the volume of burned timber (m^3/ha), "R" is the rotation age, "C" is the percent of non-commercial timber, "A_p" is the annual production (kg/ha), "P_r" is the estimated resource price (€/kg), "V" is the annual income given the carrying capacity of the site (€/ha), "n" is the estimated number of years until recovery (vegetation resilience), "St" is the reproductive stock (€/ha), "CS" is the carbon stock when the fire occurs, "P_c" is the carbon price and "AS" is the annual growth rate on carbon storage.

This work goes beyond an economic valuation approach because of the integration of the economic valuation of forest resources as well as the net value changes (NVC) [30]. Fire intensity is difficult to measure and validate in field samplings. In this sense, flame length, which is directly related to fire-line intensity [44], can be used as a good indicator of the fire impacts. Flame length is the distance measured from the average flame tip to the middle of the flaming zone at the base of the fire. Visual Fuego [39,40] was used to calculate flame length using weather information from FMC scenarios (S1, S2 and S3) and GIS information to analyze topography and vegetation characteristics. According to flame length and its relationship with fire intensity [44], six intervals or fire intensity levels (FILs) can be represented for easier managerial decision-making. FILs are related to flame length intervals using a percentage depreciation or NVC ratio to estimate the economic susceptibility of each resource [3,20,22,33,34]. Seventeen fires from 1993 to 2015 were used to test the depreciation ratios for each FIL and to identify vegetation resilience (Huétor fire, 1993; Aznalcollar fire, 1995; Los Barrios fire, 1997; Estepona fire, 1999; Cazorla fires, 2001 and 2005; Aldeaquemada fire, 2004; Minas de Rio Tinto fire, 2004; Alajar fire, 2006; Gaucin fire, 2006; Obejo fire, 2007; Orcera fire, 2009; Cerro Vértice, 2011; Coín fire, 2012; Montoro fire, 2013; Alhama fire, 2014; Quesada fire, 2015). GIS allows us to estimate economic susceptibility from fires under the three future FMC scenarios (S1, S2, S3) according to economic valuation of the resources, fire behavior and vegetation resilience.

2.5. Suppression Costs from Forest Fires

The development of a database about suppression resources costs (number of resources and hours in firefighting operations) is difficult, mainly in old wildfires. It is not common in worldwide forest fires statistics to have information about the number of working hours of each suppression resource. For this reason, the studies comparing the costs of suppression over time are a challenging task. However, we have been able to reconstruct the suppression costs of eight large forest fires that occurred in Andalusia region in the last 25 years (between 1993 and 2015). The large fires were as follows: Beas fire: 6176 ha in 1993 (A), Cázulas-Otívar fire: 2258 ha in 1999 (B), Sierra de Lújar fire: 1207 ha in 2000 (C), Mijas fire: 2295.98 ha in 2001 (D), Obejo fire: 4979.15 ha in 2007 (E), Mijas fire 1704.5 ha in 2011 (F), Coín-Marbella fire: 8226 ha in 2012 (G) and Quesada fire: 9760.42 ha in 2015 (H).

For each fire, a dataset was built with type and number of firefighting resources, number of hours worked and official cost by hour of each terrestrial and aerial resource (Supplementary Material 2). Only suppression costs to control the fire were considered, ignoring the travel costs and liquidation costs. Based on the costs dataset, the total suppression cost, the mean cost of terrestrial and aerial resources, the cost per unit area (€/ha) and the cost per unit time were calculated (€/h). We have included a comparative analysis of suppression costs in Andalusia region between 1993 and 2015 in order to identify the climate change effects in relation to suppression costs. SPSS 10© software was used in all analyses. *t*-test was used to determinate if significant differences ($p < 0.05$ and $p < 0.1$) existed in suppression costs between 1990–2005 period (A, B, C and D fires) and last decade (2005–2015 or E, F, G and H fires).

3. Results

3.1. Climate Scenarios Development

Eleven of the 17 downscaling techniques had temperature errors of less than 1 °C for the study area. The Cokigring technique with two datasets (altitude and aspect) had the best results based on the mean absolute error (MAE) and standard deviation from all weather stations used in validation (Figure 2). The 17 downscaling techniques had MAE of less than 4% for relative humidity. In this case, the Cokigring method with two variables (altitude and slope) had the most reliable outcomes (Figure 3).

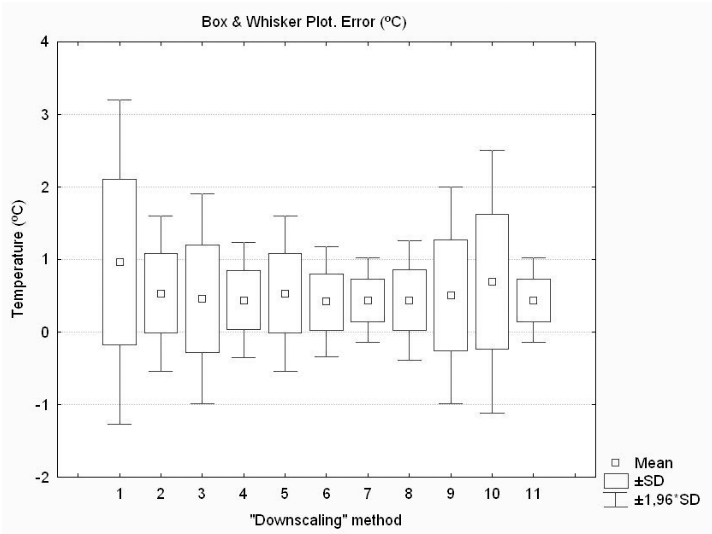

Figure 2. Estimated mean absolute errors (MAE) for temperature using different deterministic and geostatistical methods. The 11 methods used were: (1) Inverse Distance Weighting; (2) Global Polynomial Interpolation; (3) Local Polynomial Interpolation; (4) Kriging; (5) Cokriging (altitude); (6) Cokriging (altitude, forest area); (7) Cokriging (altitude, aspect); (8) Cokriging (altitude, slope, forest area); (9) Cokriging (altitude, slope); (10) Cokriging (slope, aspect); (11) Cokriging (altitude, slope, aspect).

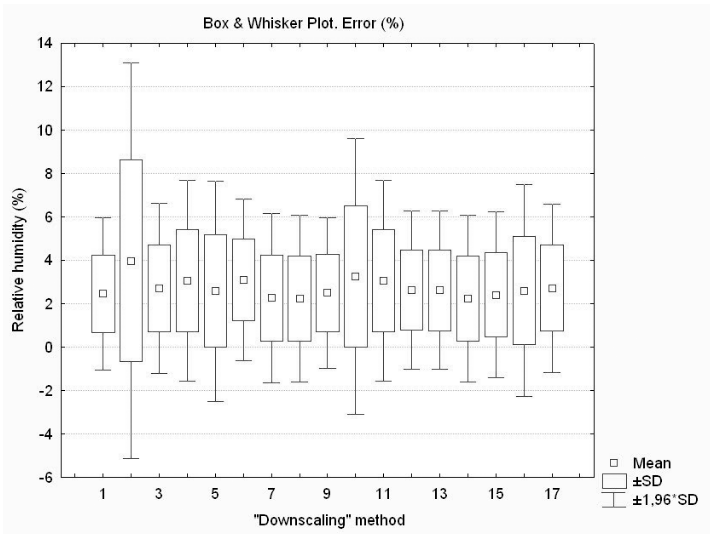

Figure 3. Estimated mean absolute errors (MAE) for relative humidity using different deterministic and geostatistical methods. The 17 methods used were: (1) Global Polynomial Interpolation; (2) Inverse Distance Weighting; (3) Local Polynomial Interpolation; (4) Kriging; (5) Cokriging (altitude, aspect); (6) Cokriging (altitude); (7) Cokriging (altitude, slope, wind speed); (8) Cokriging (altitude, slope); (9) Cokriging (altitude, slope, aspect); (10) Radial Basis Functions; (11) Cokriging (altitude, slope, canopy cover); (12) Cokriging (altitude, slope, forest area); (13) Cokriging (altitude, aspect, forest area); (14) Cokriging (altitude, slope, wind direction); (15) Cokriging (altitude, slope, valley bottom); (16) Cokriging (slope, aspect); (17) Cokriging (altitude, slope, watersheds).

The CNCM3 estimated an average summer temperature increase between 1.8 and 2.2 °C for the most unfavorable scenario (S1) and an increase between 0.4 °C and 0.8 °C for the most favorable scenario (S3) with respect to the baseline period of 1961–2000. The relative humidity decreased for S1 and S3 scenarios between 6.4% and 9.6% and between 1.8% and 2.8%, respectively. These temperature and relative humidity ranges responded to the size and topographical heterogeneity of the study area.

Our field samplings included a wide range of meteorological conditions according to the most favorable and unfavorable weeks of the period 2005–2018. For precipitation, RCPs change and uncertainty could be found to be large in regions of the world that receive heavy rainfall. In our study area, the summer precipitation (from June to September) is very low (only between zero and three rainy days) (Supplementary Material 3). We have considered zero precipitation in the last 15 days to fuel moisture estimation under actual and projected climate change scenarios. The minimum annual LFMC from summer period ranged from 47.2% to 108.3% for shrubs, and from 65% to 142.6% for trees (Supplementary Material 1). FFMC ranged from 2.78% to 12.1%. We developed two equations to calculate FFMC based on fuel shading: Equation (1) (<50% shading) and Equation (2) (>50% shading) according to 279 summer samples. While Equation (1) had a MAE of 0.89%, Equation (2) showed a MAE of 0.86%.

$$FFMC = 1.105 + 0.206H - 0.061T \qquad R^2 = 0.813 \tag{1}$$

$$FFMC = 7.919 + 0.119H - 0.101T \qquad R^2 = 0.834 \tag{2}$$

where FFMC is the fine dead fuel moisture (%); H is the relative humidity (%) and T is the temperature (°C).

We developed, as discussed earlier, three FMC scenarios (S1, S2, and S3) according to the more or less changes of climate change on FFMC and LFMC (period 2041–2070). These are summarized below.

- Scenario S1: the change in temperature and relative humidity was the largest (increase of 1.8–2.2 °C and decrease of 6.4%–9.6% with respect to the baseline period of 1961–2000), and as a consequence, the decrease in LFMC was estimated between 8% and 18% according to the dominant species and topographic variables. For FFMC, equations predicted a decrease of 1%–2%.
- Scenario S2: a drop in the FFMC of 0.7%–1.5% caused by an increase in temperature (1.3%–1.5 °C with respect to the baseline period of 1961–2000) and a decrease in relative humidity (3.3%–5.1%). LFMC could decrease between 5% and 14% according to the dominant species and topographic variables.
- Scenario S3: equations predicted a decrease of 0.5%–0.8% for the FFMC according to the smallest changes in temperature (0.4%–0.8 °C with respect to the baseline period of 1961–2000) and relative humidity (1.8%–2.8%). LFMC showed a slight decrease from current conditions (0%–5%), but without affecting significantly fire behavior.

3.2. Fire Behavior

According to the comparative analysis of fire behavior simulations between the baseline period (1961–2000) and the three future FMC scenarios (S1, S2 and S3), increases in spread rate and flame length were reported. As an example, Supplementary Material 4 shows the spread rate and flame length differences between the baseline period and S1 scenario for 145 random points. While the average increases in spread rate ranged from 3.35 m/min (S3 scenario) to 12.63 m/min (S1 scenario), the flame length increases varied between 0.22 m (S3 scenario) and 0.94 m (S1 scenario). In regard to these increases in flame length, FIL area was varied by each scenario (Table 4). While the highest area for FIL6 (9.69%) was obtained in S1 scenario, the minimum area for FIL1 (0.45%) was reached under S1 and S2 scenarios. However, the greatest changes were observed in the transition between FIL2 and FIL3 (Table 4). There were significant statistical differences between the baseline period and S1 scenario in relation to spread rate ($F = 2.75$, $p < 0.1$), flame length ($F = 2.77$, $p < 0.1$) and fire-line intensity ($F = 6.6$, $p < 0.05$). Furthermore, there was a significant statistical difference ($F = 3.27$, $p < 0.1$) between the baseline period and the intermediate scenario in relation to fire-line intensity.

Table 4. Fire intensity level (FIL) area **(%)** estimated to the baseline period and the FMC scenarios.

Flame Length (m)	FIL	Baseline (%)	S1 (%)	S2 (%)	S3 (%)
<2	I	0.47	0.45	0.45	0.47
2–3	II	44.43	9.62	43.44	43.44
3–6	III	27.08	59.93	25.77	27.39
6–9	IV	14.19	3.90	8.76	7.58
9–12	V	11.15	16.40	14.03	13.56
>12 m	VI	2.69	9.69	7.56	7.56

3.3. Economic Susceptibility from Forest Fires

Although the less severe fires (FIL I and II) could have positive effects on fire-prone ecosystems (e.g., in grassland production resource without the need of livestock exclusion for vegetation regeneration), field samplings showed increases in the NVC according to each FIL (Table 5). At large scale, the increase in flame length and fire intensity led to greater economic impacts. The economic susceptibility of the Córdoba province varied from 981,453,167€ (baseline period) to 1236,541,113€ (S1 scenario) (Table 6). For the study area, the impacts of climate change increased the potential economic impacts between 63,632,966€ (S3 scenario) and 255,087,946€ (S1 scenario) with respect to a baseline period. For the S1 scenario, the most important changes were found in firewood (65,534,622€), carbon storage (48,061,659€) and timber (41,812,106€) (Table 6). For S2 and S3 scenarios, the non-timber resources susceptibility increased between 54,230,349 € and 59,913,688 €. In these cases, the most remarkable changes were measured for the carbon storage (19,227,550–21,088,365€) (Figure 4) and the cork oak (16,944,671–18,090,473€) (Table 6).

Table 5. Net value change (NVC) (%) of each resource based on fire intensity level (FIL).

Resource	FIL I	FIL II	FIL III	FIL IV	FIL V	FIL VI
Timber [1]	8.33 (±6.58)	16.65 (±5.89)	38.58 (±6.27)	57.85 (±13.74)	82.79 (±1.81)	89.41 (±2.82)
Firewood [2]	4.5 (±0.71)	9 (±1.41)	18.2 (±4.25)	52.5 (±10.61)	66.1 (±6.42)	77.5 (±6.53)
Fruit production [3]	5.83 (±1.44)	11.67 (±2.88)	24.67 (±9.23)	48.75 (±1.76)	68.16 (±1.60)	80.17 (±1.25)
Cork oak [4]	7.5 (±3.53)	15 (±7.07)	30 (±21.21)	47.5 (±24.74)	67.5 (±14.73)	80 (±14.14)
Pasture [5]	-	-	85	100	100	100
Game [6]	20	45	65	85	95	100
Carbon storage [7]	58.02 (±11.89)	58.02 (±11.89)	70.38 (±12.05)	83.7 (±4.28)	98.75 (±2.62)	98.75 (±2.62)

[1] NVC obtained from [23] [2] NVC obtained from [33] and the following new experiences: Orcera fire (2009), Cerro Vértice fire (2011), Coín fire (2012), Montoro fire (2013), Alhama fire (2014) and Quesada fire (2015) [3] NVC obtained from [42] and the following new experiences: Cerro Vértice fire (2011), Coín fire (2012), Montoro fire (2013), Alhama fire (2014) and Quesada fire (2015) [4] NVC obtained from [45] [5] NVC obtained from [42] and the following new experiences: Montoro fire (2013) and Quesada fire (2015) [6] NVC obtained from [43] [7] NVC obtained from [25].

Table 6. Economic susceptibility of Córdoba province according to the baseline period and S1, S2 and S3 scenarios.

Resources	Scenarios			
	Baseline Period (€)	S1 (€)	S2 (€)	S3 (€)
Timber resources	209,465,938	251,278,044	220,149,121	218,868,555
Firewood	202,849,328	286,383,950	219,508,148	217,581,960
Pine nut	12,672,785	14,550,164	13,525,409	13,459,315
Acorn fruit	75,337,855	111,376,160	77,695,222	77,166,375
Chestnut	36,842	37,249	37,249	36,842
Cork oak	182,061,413	215,807,738	200,151,886	199,006,084
Pasture (grazing activity)	49,368,734	72,126,915	49,455,449	49,445,321
Game (hunting activity)	32,761,162	38,020,124	33,539,809	33,395,021
Carbon storage	216,899,110	264,960,769	237,987,745	236,126,660

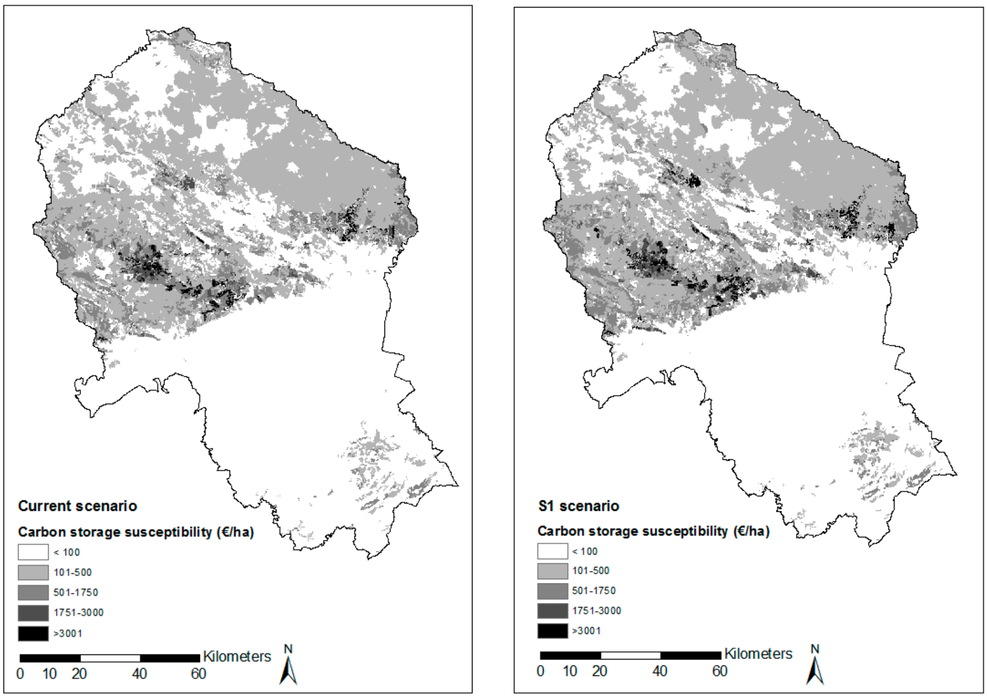

Figure 4. Economic susceptibility of carbon storage under baseline period and S1 scenario for Córdoba province.

3.4. Suppression Costs from Forest Fires

The suppression costs of both terrestrial and aerial resources increased sharply at the beginning of the 21st century. Because of this, the cost per unit area and the cost per unit time between Fire A and Fire H showed an increase of 86.73% and of 65.67%, respectively (Table 7). Significant statistical differences were found between fires that occurred between 1995–2005 and fires that occurred in the last decade (Table 8) in relation to the number of hours worked to control the fire ($t = -0.99$, $p < 0.05$), aerial resources costs ($t = -1.86$, $p < 0.05$), total suppression costs ($t = -1.68$, $p < 0.1$) and suppression cost per unit time ($t= -1.88$, $p < 0.1$).

Table 7. Suppression costs for each large fire studied.

Forest Fire	A	B	C	D	E	F	G	H
Burned area (ha)	6176.00	2258.00	1207.00	2295.98	1704.50	8226.00	4979.15	9760.42
Control time * (h)	57.00	53.00	51.00	36.00	36.00	42.00	72.00	233.00
Burned area/hour (ha/h)	108.35	42.60	23.67	63.78	47.35	195.86	69.15	41.89
Terrestrial resources (€)	115,749.44	118,489.00	123,940.72	373,646.69	103,654.72	134,659.26	198,837.06	240,775.86
Aerial resources (€)	64,909.31	176,912.48	111,863.98	89,138.28	239,222.10	375,357.87	748,162.17	1,910,652.73
Total suppression costs (€)	180,658.75	295,401.48	235,804.70	462,784.97	342,876.82	510,017.13	946,999.23	2,151,428.59
Cost per unit area (€/ha)	29.25	130.82	195.36	201.56	201.16	62.00	190.19	220.42
Cost per unit time (€/h)	3169.45	5573.61	4,623.62	12,855.14	9524.36	12,143.26	13,152.77	9233.6

(A) Beas fire: 6176 ha in 1993, (B) Cázulas-Otívar fire: 2258 ha in 1999, (C) Sierra de Lújar fire: 1207 ha in 2000, (D) Mijas fire: 2295.98 ha in 2001, (E) Obejo fire: 4979.15 ha in 2007, (F) Mijas fire: 1704.5 ha in 2011, (G) Coín fire: 8226 ha in 2012 and (H) Quesada fire: 9760.42 ha in 2015. * Control time: is the time of reducing the heat output of a fire, extinguishing the fire by the completion of a control line around the perimeter.

Table 8. Average suppression costs from large fire experiences in Andalusia Region.

Forest Fire	Large Fires (1990–2005)	Large Fires (2005–2015)
Burned area (ha)	2984.24 (±2186.86) [a]	6167.52 (±3581.29) [a]
Control time (h)	49.25 (±9.18) [a,*]	95.75 (±92.84) [b,*]
Burned area/hour (ha/h)	59.60 (±36.39) [a]	88.56 (±72.49) [a]
Terrestrial resources (€)	182,956.46 (±127,172.40) [a]	169,481.72 (±61,888.04) [a]
Aerial resources (€)	110,706.01 (±48,121.87) [a,*]	818,348.72 (±759,316.08) [b,*]
Total suppression costs (€)	293,662.47 (±122,096.69) [a,**]	987,830.44 (±816,475.88) [b,**]
Cost per unit area (€/ha)	139.25 (±80.00) [a]	168.44 (±72.05) [a]
Cost per unit time (€/h)	6555.45 (±4314.59) [a,**]	11,013.5 (±967.75) [b,**]

* Mean values in a row followed by the same letter are not significantly different ($p < 0.05$). ** Mean values in a row followed by the same letter are not significantly different ($p < 0.1$).

4. Discussion

The climate scenarios generated for the first seven decades of the century present robust estimates for temperature [13,16]. RCP 2.6 changes are much lower than the rest of the RCPs because it includes the option of using policies to achieve net negative carbon dioxide emissions before the end of the century [16,36]. Geostatistical methods using GIS play an important role for extrapolating the climate scenarios to any territory [33–35]. Results for our study area shows an increase in the summer temperatures similar to those obtained in other Mediterranean studies [8,16,18,46]. In recent summers, field inventories in Mediterranean basin have shown values generally smaller than standard values observed for FFMC and LFMC [47,48]. According to our results, FFMC and LFMC could decrease between 0% and 2% and between 8% and 18%, respectively. The decrease in FMC has an important effect on fire behavior, and as a consequence, in the large fires' occurrence [1,3,4,19–22]. The integrated use of GIS and fire spread simulators allows us to analyze fire behavior under different FMC scenarios [39–41]. Our FMC scenarios showed more severe fire behavior in a similar way than other studies [1,19,20]. Flame length increased from 4.60% to 15.69%, and as a consequence, fire-line intensity increased considerably, ranging from 9.81% to 21.31%. Finally, climate change would raise spread rate between 4.45% and 24.07%. Some studies have shown the effects of climate change in fire intensity and difficulties in suppression flames [10] and, therefore, in an increase in the economic impacts from wildfires [6,9,24,25].

The goal of this manuscript has not been to make a dissertation on the consequences of climate change on the socioeconomics of potentially affected Mediterranean ecosystems. However, we consider that the effects of climate change in increasing the intensity and severity of forest fires, imply a greater demand for budgets to increase the contracting of resources from suppression activities. It also implies an increase in the duration of contracts over the months. The effects are of a reduction in the same proportion of the budget allocated to fire prevention and management activities in the fuel treatment. The administrations and departments of prevention and extinction of forest fires have difficulties to obtain increases of budgets to extinction and fire suppression without affecting in reductions in the budgets of prevention. This circumstance is today a reality verified throughout the last 50 years. In addition, and as already demonstrated in the manuscript, the increase in the difficulty of suppression actions is generating a progressive increase in suppression costs.

Unquestionably, the increase in the intensity and severity of forest fires due to climate change [1,9,40] and the high availability of forest fuels (abandonment of the rural environment and decrease in population density) would increase natural resources impacts. In this sense, disturbances and negative effects affect the income of populations when resources such as leisure and recreation are damaged by the strong alteration of the landscape after the fires, in the same way erosion and loss of water quality, are damages in forest landscapes that indirectly imply negative effects on the socioeconomics of the populations affected. On the other hand, one might think that forest restoration work on landscapes affected by fires can be a positive consequence from a socioeconomic point of view, increasing the wages and jobs in the rural economy. This is not entirely true for two reasons: first, the strong budgetary decapitalization of governments and administrations makes it difficult to approve budgets in order to address the financing of restoration work on the large areas affected by large forest fires. Consequently, the generation of job opportunities is not clear. Secondly and from the point of view of investigations of the causes of the forest fires over more than 50 years, important efforts have been made to avoid relating forest fires to the socio-economic benefit of increasing wages for extinction, prevention and the restoration. These control actions are aimed at reducing the arson fires causes. From our point of view, it is difficult to find positive socio-economic effects of climate change on forest fires. Perhaps it could be indicated as a positive effect, the change in the combustibility that occurs in the landscapes affected by large fires, decreasing of high intensity fires in the following decades, so the slow recovery of damaged resources. It will be guaranteed in one way or another, as well as the protection and defense of populations located in forest areas.

The economic susceptibility of the forest resources in the study area is about 918 million Euros according to the baseline period. Fire impacts pointed to the importance role that carbon storage (22.10% of the total loss), timber (21.34%) and firewood (20.67%) resources play in the rural study area. The effect of climate change on individual resources is uneven. For example, while acorn production impact increases considerably (Table 6), chestnut production impact is slightly affected, due in part to its location in humid areas filled with debris and isolated understory. Some resources, such as cork oak, pasture production and game, have shown few changes under the favorable and intermediate scenarios (S2 and S3 scenarios), but larger changes for the most unfavorable scenario (S1 scenario). As an example, a livestock exclusion is needed in pasture production resource for the highest fire intensity levels [41,44]. It can be observed in the differences between baseline period, S2 and S3 scenarios and S1 scenario (an increase of 46% of the economic impacts). In general, climate change would increase the economic susceptibility of the study area between 63,632,966€ or 6.05% (baseline period-S3 scenario) and 255,087,946 or 25.99%€ (baseline period-S1 scenario) (Table 9).

Table 9. Economic susceptibility differences according to the baseline period, S1, S2 and S3 scenarios.

Scenarios	Economic Susceptibility (€)	Increase	
		€	%
Baseline	981,453,167	-	
S1	1,236,541,113	255,087,946	25.99
S2	1,052,050,038	70,596,871	7.19
S3	1,045,086,133	63,632,966	6.05

Climate change has accentuated the virulence and the suppression of difficulties of large fires leading to an increase of suppression costs [27–29,49]. Although there is a wide burned area range according to the standard deviation, an upward trend can be seen in the last decade in relation to burned area (6167 ha compared with 2984 ha) and burned area per unit time (88.56 ha/h compared with 59.60 ha/h) (Table 6). These burned area trends and the significant statistical difference found in the control time (95.75 h compared with 49.25 h) seem to suggest that there is an increase in suppression difficulties [26]. Significant statistical differences were found between 1990–2005 large fires and 2005–2015 large fires from total suppression costs and suppression costs per unit time. The comparative analysis confirmed a general increase in cost per unit area (86.73%) and cost per unit time (65.67%), mainly in relation to the increase in aerial resources cost (818,348€ compared to 110,706.01€). This increase in aerial firefighting operations responds both to the number of aircraft and to the number of hours worked between the two time periods considered. According to fire size costs, we found an average rate of 1.41-fold increased suppression costs between the two time periods considered. It is an interesting outcome that suppression costs have increased in recent years in association with a decrease on FMC was induced by an increase in temperature and a decrease in relative humidity.

Suppression costs are based on the real data and official prices for the study area. In this sense, our findings highlight the increase of suppression costs in the last decade. The average suppression cost per fire size [49] can offer the possibility to study in depth the behavior of the suppression costs over time based on fire size. Measuring techniques would have most likely greatly improved for the time period considered (2041–2070). Although fire suppression techniques have improved from 1990 to 2019, fire suppression costs have increased as reported in this and other studies [27–29,49]. However, increase fire suppression efficiency has not been demonstrated in part due to the generalized decision to send more and more fire suppression resources to fires without knowledge of the resources' efficiency [50,51]. This practice is more evident in high-intensity large wildfires increasing fire suppression costs without a corresponding increase in suppression activities efficiency.

At present, fire suppression costs for the study area in general represent about 65% of the total fire management budget [52]. The increase in fire intensity leads to higher economic impacts and suppression difficulties [6,10,24,25], which if not considered leads to higher suppression costs [1]. Our research only considered suppression costs' changes. Further studies should include the prevention costs and the relationship between prevention and suppression efforts and costs. Because the important short- and long-term effects and the higher risk of large fires, the national and regional agencies and/or authorities have requested estimations on fire susceptibility and suppression difficulties of wildfires in relation to climate change. Our approach identifies sectors and resources with the highest future economic susceptibility for the considered period (2041–2070). This strategic information plays an essential role in operational priorities and firefighting resources management to increase the efficiency in the provision of fire services and to mitigate the fire impacts. The use of GIS tools increases the flexibility of this approach to include new forest resources and net value changes enabling a further extrapolation to any study area.

5. Conclusions

Climate change plays a key role in the medium- and long-term forest fire management. There is a future upward trend in the number and frequency of large fires that looms even larger because of the higher spread rate, flame length and fire-line intensity according to the climate change scenarios used here. The potentially resulting fire regime leads to significantly increased economic fire impacts, fire suppression difficulties, and fire suppression costs, mainly in relation to aerial firefighting resources. Climate change should be considered in fire-management policies for mitigation and adaptation of potential economic susceptibility by prioritization of fuel treatments. The economic susceptibility of the territory in the medium term (2041–2070) allows us to optimize preventive activities and to find an efficient spatial-temporal allocation of suppression resources. The availability of GIS eases the possibility to make changes and adaptations given new or updated climate scenarios and different management needs, making it a valuable tool in fire management and prevention programs.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/10/8/679/s1: Electronic Supplementary Material 1: live fuel moisture for fire behavior simulation, Electronic Supplementary Material 2: inputs data for assessing suppression costs, Electronic Supplementary Material 3: potential effects on spread rate and flame length, Electronic Supplementary Material 4: Potential effects on flame length.

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