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Abstract: While the Mediterranean basin is foreseen to be highly affected by climate change (CC) and severe forest fires are expected to be more frequent, international efforts to fight against CC do not consider forest fires' greenhouse gas (GHG) emissions risk and the possibility of its mitigation. This is partly due to a lack of a methodology for GHG risk spatial assessment and consideration of the high value of carbon stocks in forest ecosystems and their intrinsic risk. To revert this, an innovative GHG emission risk model has been developed and implemented in a pilot forest area. This model considers geospatial variables to build up emission vulnerability based on potential fire severity and resistance of a landscape, value at risk and the hazard of a fire occurrence. The results classify low, moderate and high emission risks in the analysed areas. This identification of hotspots allows the prioritisation of fire prevention measures in a region to maximise the reduction of GHG emissions in the case of a fire event. This constitutes the first step in a holistic and consistent CC mitigation that not only considers anthropic GHG sources but also possible GHG emissions by forest fires that can be actively prevented, managed and reduced.

Keywords: greenhouse gas emissions; forest fires; emission vulnerability; carbon stocks; emission risk model; hazard; damage

1. Introduction

Wildfires are a dominant disturbance factor in almost all forest vegetation zones throughout the world and represent important emissions of gaseous and particulate compounds into the atmosphere with serious physical, biological and environmental impacts [1].

The Mediterranean region is one of the "hot-spots" of climate change [2]. In this area, wildfires have a significant impact, burning approximately 0.5 million every year in the five southern EU member states (Portugal, Spain, Greece, Italy and France) [3].

The Mediterranean region is characterised by hot and dry summers, high diversity of plant species and unusual geographical/topographical variability related to the presence of a jagged coastline and many mountain ranges, often rather steep. Since 1960, wildfire occurrence has increased because of changes in land use, which resulted in extensive land abandonment, increases in the fuel load and continuity in the landscape [4]. These factors are considered to be the main drivers of increased wildfire occurrence and the resulting risk of soil degradation [5–12].

Moreover, the current climate has a large influence on wildfires, especially in extreme conditions [13,14]. An increase in the duration and severity of heat waves [15,16] has caused a dramatic increase in fire incidence in Mediterranean regions during recent decades, and fires are expected to become more prevalent in the future due to climate change [17].

When weather conditions are particularly severe (e.g., heat waves or very hot and dry summers combined with strong winds) forest fires may reach catastrophic proportions, so-called megafire events, producing not only a loss of biodiversity, soil erosion and desertification [9], large economic losses and threats to human lives but also noteworthy GHG emissions in the atmosphere [18].

The greenhouse gases and particulate matters directly influence climate [19,20] due to the release of various types of gases and aerosols into the atmosphere because of the combustion of biomass during forest fires, which have a significant impact on atmospheric chemistry, biogeochemical cycles and climate [21]. Not only do many of these gases contribute to climate change and the process of the greenhouse effect, but they can also trigger many other repercussions. This disturbance also implies a change in the dynamics of the gross primary production and ecosystem respiration. It also leads to net ecosystem production losses continuing for several years after the event, which is followed by a sustained multidecadal period of net ecosystem carbon uptake [22].

It is known that tremendous efforts are being performed at international political, regulatory and technological levels to reduce carbon emissions, with binding and non-binding compromises and high objectives of emission reductions on a worldwide scale [23–25] and at the European level [26–28], but there is no common policy on forest fire management and its prevention.

Recently, in 2021, the European Commission adopted a New Strategy for the European Union in favour of forests for 2035 [29] in which it is considered necessary to reduce the risks for forests in the context of uncertainty due to climate change through appropriate adaptation measures and forest management practices that strengthen resilience. For this, not only must technical knowledge be developed but also incentives and regulatory support must be offered.

There are many studies on ecological risk assessments [30] related to fire hazards, assessing the risks to ecosystem services from forest fires [31] or fire smoke risk on populations [32]. There is also very extensive literature on fire risk assessment [33–37] and fire danger in the Mediterranean basin using coarse-scale fire danger indices, such as the Canadian Forest Fire Weather Index (FWI) [38,39], the Wildland Fire Assessment System (WFAS) [40], the Forest Fire Danger Index (FFDI, also called Mark 5 the Burning Index, BI), the KBDI [41], etc. These indices rely solely on weather information or statistical models of climate and vegetation [42–48].

The fine-scale patterns in fire behaviour are important from a risk standpoint and can be assessed using a number of innovative approaches developed in recent decades for estimating and mapping wildfire risk and exposure [37,42,49–52]. These approaches use quantitative wildfire risk assessment [51] and employ a number of relatively new, large, fire modelling systems. Nevertheless, there are no studies assessing greenhouse gas emission risk from a preventive perspective with the aim of managing it to reduce emission risk impacts on the climate from forest fires. Therefore, the general objective of this study is to set the basis for a qualitative spatial assessment of forest fire emissions risk.

2. Materials and Methods

2.1. Basis of the Model

IPCC [53] defines the concept of risk as "the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems". According to [54], risk can be defined as a combination of hazard and damage; therefore, the Emission Risk assessment model can be defined as (Equation (1)):

$$\text{Emission Risk} = \text{Hazard} \times \text{Damage} \tag{1}$$

where hazard (H) is the potential forest fire risk and shows the probability of a fire event [55] and depends on two variables: Statistical risk and site danger (composed of fire recurrence, cause and exposure). In this model, a hazard is taken as the probability of emissions due to forest fires (recurrence), expressed as the fire frequency as it indicates the risk of ignition. The cause is not relevant in terms of the risk of emission, and the exposure to fire is included as part of the other variables.

Damage (D) is the consequence in terms of GHG emissions from the stored carbon in the analysed ecosystem as a result of combustion produced by a forest fire [54]. The damage degree depends on the value at risk, in this case, total carbon from vegetation and soils stored in the ecosystem, and its vulnerability to emitting GHG emissions.

$$\text{Damage} = \text{Value at risk} \times \text{Emission vulnerability} \tag{2}$$

Value at risk (VAR) is defined as the potential loss due to an adverse event [54]. In the REMAS context, the VAR variable includes carbon fixed in both vegetation and soils. It is the carbon stock of the ecosystem and represents the total carbon stored, which is available to be released into the atmosphere as CO_2 emissions as a consequence of a forest fire [18].

Emission Vulnerability (EV), as defined above, is the degree of loss or damage that carbon stored in an ecosystem may cause in a wildfire event, materialised in GHG emissions. According to [56], this process depends on two main factors: The resistance of the ecosystem to fire ignition and propagation through the stand (potential fire resistance) and the degree of loss based on the intensity of the fire (potential fire severity).

2.2. Factors of Interest

The effects of carbon emissions are influenced by fire intensity and severity [57], which depend on an interaction between different factors that can vary a great deal depending on the place and the time of the year. These variables are considered in many studies [33,34,36,42,58] and are summarised as topography, weather conditions, forest fuel types and vegetation.

On the other hand, the impact of forest fires can be controlled and reduced with silvicultural treatments. Studies have demonstrated that fuel reduction treatments, among others, can reduce carbon losses in the case of a wildfire [59–62].

2.2.1. Fire Frequency

This is the indicator of the probability of a fire occurring based on the quantification of forest fires registered in a period of time and a determined spatial unit [63]. According to [18,58], the higher the fire frequency, the higher the emission risk envisaged. Its calculation is performed according to [64]. Its value assessment in terms of emission risk can be found in Table A1.

2.2.2. Ecosystem Carbon Stock

This variable is composed of the different carbon sinks that can be found and from which data are available in forest ecosystems. According to [65], the more carbon is stored, the more emission risk is envisaged. Its value assessment in terms of emission risk can be found in Table A2.

- Vegetation carbon stock

It considers the total carbon stored in vegetation as tonnes (Mg) of carbon per hectare. Databases are obtained from the quantification of carbon stored in the main forest tree species representative of the study areas. The estimation of these vegetation carbon stocks can be obtained following several methodologies [66,67].

- Soil organic carbon stock

With soil organic carbon, we define the carbon stocks, not the soil carbon content. Soil organic carbon is the carbon contained in soil organic matter, but stocks refer to a volume. Therefore, according to [68], it considers the mass of carbon in a sample of known bulk density. Soil organic carbon stocks are generally expressed in tonnes (Mg) per hectare for a nominated depth (from 0–30 cm depth) and commonly restricted to the fraction [68] n < 2 mm in size [68]. Available soil carbon stock maps were used to estimate it.

2.2.3. Preventive Silviculture (PS)

Preventive silviculture manages forests by enhancing their capacity to protect themselves from fires by creating discontinuities, avoiding very extensive, monospecific surface areas and creating a patchwork of different inflammability levels that disturb the fire [69]. This can be achieved through fuel treatments for biomass reduction, which are paramount to wildfire abatement [70]. In the model, two main factors have been considered:

- Prescribed burns (PB)

This can be defined as the controlled use of fire to reduce vegetation under specific conditions that allow for setting the intensity of the fire and the amount of vegetable fuel to be eliminated according to a proposed objective [71]. The existence of prescribed burns is foreseen to lead to lower emission risk [17,71].

- Vegetation treatments (VT)

The objective of vegetation treatment is to improve the conditions of life, growth and health of the forest stand. According to [72], it helps to reduce fire spread because it reduces vertical and horizontal biomass continuity. These practices include treatments applied to tree and shrub vegetation but also to the soil [72]. The main fire preventive treatments are auxiliary strips, tree clearing and thinning and shrub clearing.

Both PB and VT are assessed in terms of emission risk according to Table A3. The existence of vegetation treatments is envisaged to lead to lower emission risk [60,73,74].

2.2.4. Infrastructure (I)

This consists of artificial facilities for forest fire prevention. This infrastructure can be of help in the case of forest fires with dimensions within the extinction capacity of forest services [75]. In this case, firebreaks and fuelbreaks, road infrastructure and the water supply network accounted for the model with the following approach:

- Firebreaks and fuelbreaks network (FN)

Firebreaks are defined as strips or elongated spaces with a width of 20 to 30 m in which all types of vegetation are removed, exposing mineral soil [72], while fuelbreaks have a biomass decrease associated with a fuel model change. Both nets are constructed on artificial lines, such as paths, boundaries of mountains or forest planning units; on natural lines such as maximum line slopes coinciding with the separation of rain gaps; and on summit lines, although in this case, they should be located not on the hills but rather in areas set back above the beginning of the slopes, where the wind speed is relatively low [69,72]. They have a double objective of acting as a barrier for the propagation of the fire and as a physical support for firefighters and extinction media to perform their work.

- Road network (RN)

Different types of forest roads (road infrastructure) are distributed throughout the terrain. These paths have a double impact in relation to forest fires. On one hand, they act as a physical barrier to the spread of the fire. On the other hand, they act as an operative point where firefighters and extinction media can perform their work [76].

The firebreaks and forest road networks are merged in order to be included in the model since they often designate the same physical element. The existence of firebreaks and forest roads is envisaged to lead to lower emission risk [76,77].

- Water supply network (WSN)

There are different types of water sources distributed throughout the terrain in order to cover the maximum surface to provide water in the case of fire [78]. This network is of help for fire extinction bodies in the case of a fire event, and therefore its presence contributes to fire suppression with a consequent emission reduction.

In order to calculate the area of influence of the water supply points, the buffer area established was 2500 m. The existence of water supply points is foreseen to lead to lower emission risk [78].

FN, RN and WSN were assessed in terms of the emission risk according to Table A3.

2.2.5. Spatial Heterogeneity (SH)

This is the spatial variability of different ecosystems in a determined landscape. This mosaic acts as a natural barrier opposing fire propagation [79]. It depends on two main factors: The spatial distribution of land uses in a determined unit (Landscape) and the continuity derived from the different ecosystem structures present in that landscape (Ecosystem). Landscape and Ecosystem factors have been calculated using the Fire selectivity Index (SI) [80], which is an indicator of land cover types that are positively selected by fire.

- Landscape (L)

This is defined as the number of different values of the fire Selectivity Index (SI) in a determined spatial unit, determined by the area occupied by each of them [81]. It is measured through the "Shannon-Wiener Index" (H'), which is an indicator of landscape heterogeneity [81]. It is formulated as (Equation (3)):

$$H' = -\sum_{i=1}^{S} (P_i \times P_i) \quad (3)$$

where:

S = number of different SI values.

P_i = occupied proportion of each SI with respect to the total surface.

The existence of a mosaic with different SI values (higher values of H') is envisaged to lead to lower emission risk [79]. The landscape-assigned values in terms of the emission risk are classified according to Table A4.

- Ecosystem (E)

This indicates the horizontal continuity of the different land uses, especially for those that are positively selected by fire, as a factor that facilitates the propagation of a fire. It is measured through the "Aggregation Index" (CONTAG), which expresses the degree of aggregation of the elements of a landscape [82]. It is formulated as (Equation (4)):

$$\text{CONTAG} = [1 + \sum\sum[[(P_i)[g_{ik}/\sum g_{ik}]] \times [\ln(P_i)[g_{ik}/\sum g_{ik}]]]/2 \times \ln(m)] \quad (4)$$

where

m: The number of different Sis.

P_i: The proportion of the total surface occupied by a determined SI.

g_{ik}: The number of adjacencies between spot types (SI) i and k.

The bigger and more aggregated the SI patches are (lower values of CONTAG), the more horizontal continuity and emission risk are envisaged [72]. Table A5 shows the classification of emission risk according to the resulting ecosystem factor.

2.2.6. Fuel Model (FM)

The classification of different types of forest structures explains the behaviour of fire during a forest fire based on the length of the flame and the speed of propagation [83]. It was measured using the "Vegetation Index", which expresses the risk derived from the fuel model types (see Table A6). These risk values were obtained following the methodology in Appendix B and are dependent on the site conditions. The higher the vegetation risk, the higher the emission risk [84], so a higher value is assigned as a consequence.

2.2.7. Climatology (C)

Fire behaviour depends, to a large extent, on atmospheric weather elements [84]. However, given that the present model is intended to be used in fire prevention plans, which are drawn up for a large period of time and have a predictive nature, it is not possible to consider variables as changing as the weather [84]. For this reason, climate variables will be included in their place, which are much more stable for long periods of time.

It is assessed based on several indexes proposed by [85] in the Worldwide Bioclimatic Classification System. The driest and warmest bioclimatic regions are envisaged to be the most dangerous and the least cold and humid subtypes [84]. To do so, three indexes are calculated:

- Thermicity index (Itc)

Thermicity compensated index (for latitudes > 23°) [85] (Equation (5)):

$$\begin{gathered} \text{If Am} < 8,\ \text{Itc–} = \text{It} - 80 + 10\ \text{Am} \\ \text{If } 18 > \text{Am} > 8,\ \text{Itc} = \text{It} \\ \text{If Am} > 18,\ \text{Itc} = \text{It} + \text{C1} + \text{C2} + \text{C3} + \text{C4} \end{gathered} \tag{5}$$

where Am is the annual mean amplitude (Tmax-Tmin: Difference between the average temperature of the hottest and coldest months of the year, °C)

C1 = −(Am − 18) (0 < C1 < 15)
C2 = 1 − (Am − 21) (0 < C2 < 105)
C3 = 2 − (Am − 28) (0 < C3 < 450)
C4 = 3 − (Am − 46) (0 < C4 < 570)

The higher the thermicity index, the higher the emission risk is foreseen to be; consequently, Tables A7 and A8 show the emission risk value for this factor.

- Continentality index (Ic)

This expresses the difference between the average temperature of the hottest and coldest months of the year, measured in °C. According to [85] (Equation (6)):

$$\text{Ic} = -\text{Tmax} - \text{Tmin} \tag{6}$$

The higher the continentality (more extreme temperatures), the higher the emission risk envisaged as a consequence, as shown in Table A9.

- Ombrothermic index (Io)

This relates to precipitation and temperature according to [85] (Equation (7)):

$$\text{Io} = \text{Pp}/\text{Tp} \tag{7}$$

where:

Pp: Positive precipitation (mm) (∑ of months with $t_i > 0$ °C).
Tp: Positive temperature (°C) (∑ of months with $t_i > 0$ °C).

Table A10 shows that the higher the ombrothermic index is (humid climates), the less emission risk is envisaged.

2.2.8. Topography

This describes the relief or morphology of the terrain. There are several factors to consider regarding wildfires, such as the slope, altitude, orientation and relief. Nevertheless, only the slope and orientation were assessed since they have a decisive influence on the behaviour of the fire [84].

- Slope (S)

The slope is the topographic factor with the greatest influence on the speed of fire propagation [84]. Fire moves faster uphill. In fact, for every 10-degree increase in the slope, a fire will double in speed [86,87]. This is because the slope provides a similar effect to the wind, effectively laying the flames down into the slope and pre-heating the vegetation, allowing it to ignite more quickly [88].

Table A11 shows that the higher the slope (it accelerates the propagation of fire), the more emission risk is envisaged [84].

- Orientation (O)

This is the geographical direction that the slope faces. The orientation of a slope influences a fire's behaviour in several ways. Northern and western orientations receive more direct heat from the sun, drying both the soil and vegetation more than on southern or eastern slopes. Fuels are therefore usually drier and less dense on northern and western slopes than fuels on slopes with a different orientation [88]. In contrast, in the Northern hemisphere, Southern and Eastern orientations have drier vegetation and soils due to the more direct heat from the sun.

The Campbell Prediction System's Flammability Card [89] illustrates the potential fuel temperature variations in the five primary orientations: N, S, E, W and flats. Southern orientations are those with higher fuel temperatures and flammability, followed by the west, east and northern ones. The higher the fuel temperatures and flammability, the more emission risk is envisaged [89]. Table A12 shows the values for the orientation factor.

2.3. Model Build-Up

Figure 1 presents a general scheme of the emission risk model. In the following paragraphs, the model is described and the component variables' calculation is explained in detail.

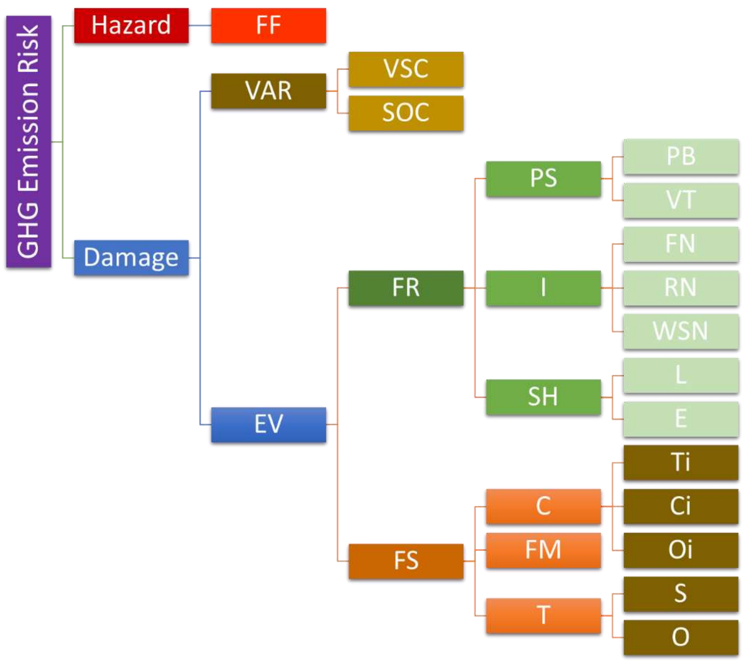


Figure 1. General scheme of the emission risk model.

2.3.1. Hazard (H)

The values of fire frequency calculated according to [64] were classified into five ranks for use as part of the Emission Risk formula adopting the values shown in Table A1.

2.3.2. Damage (D)

To calculate the damage factor, it is necessary to previously estimate the value at risk and the emission vulnerability. The final damage is the percentage of carbon that has been released by the fire event, and it depends on the ecosystem's emission vulnerability.

- Value at risk (VAR)

Carbon stock factor values have been classified into five ranks according to the percentile methodology (quintiles) to determine the classification intervals in the region.

Value at risk is formulated as Equation (8):

$$\text{VAR} = \text{Vegetation Carbon Stock} + \text{Soil Organic Carbon Stock} \tag{8}$$

- Emission Vulnerability (EV)

EV is calculated according to Equation (9)

$$\text{EV} = \text{Potential Fire Severity} \div \text{Potential Fire Resistance} \tag{9}$$

- Potential Fire Severity (FS): The term fire severity has traditionally been understood as the degree to which a site has been altered or disturbed by fire [90]. Nevertheless, most of the definitions do not consider operational metrics to assess it. According to [90], most empirical studies that have attempted to measure fire severity have had a common basis that focuses on the loss or decomposition of organic matter, both aboveground and belowground. Aboveground metrics are generally indicators of biomass loss [90,91]. On the other hand, soil characteristics include the loss of the litter and duff layers and ash characteristics, all of which reflect, to varying degrees, the level of organic matter consumed [92]. Additionally, the weather conditions and topography are the other two factors that contribute to the fire behaviour triangle that will be assessed [93]. Nevertheless, this model is intended to be used as a prediction of fire severity in future wildfire events, so other biotic and abiotic variables not related to measurements after a fire event will be considered [84].

Consequently, potential fire severity is calculated as follows (Equation (10)):

$$\text{FS} = \text{a} \times \text{Fuel Model} + \text{b} \times \text{Climatology} + \text{c} \times \text{Slope} + \text{d} \times \text{Orientation} \tag{10}$$

- Potential Fire Resistance (FR): This represents the opposition to the propagation or spread of the fire through the forest biomass [56]. It depends on the vertical and horizontal continuity of the forest biomass, which is an indicator of its combustibility [72]. At the same time, combustibility depends on several factors such as the existence of preventive silviculture and infrastructures, heterogeneity of the landscape and extinction capability of the firefighting agents and media, but also meteorological conditions, moisture content of the biomass, terrain slope and orientation, etc. Nevertheless, only the first three variables were considered in the model, integrated into a formula as follows (Equation (11)):

$$\text{FR} = \text{e} \times \text{PS} + \text{f} \times \text{PI} + \text{g} \times \text{SH} \tag{11}$$

In both equations (FS and FR), a–g coefficients are weighting parameters determined by a panel of 26 experts on silviculture, fire prevention and firefighting from academia, public and private institutions from Portugal, Spain and France, through the Analytic Hierarchy Process (AHP) [94,95].

2.3.3. Emission Risk Assessment

Applying Equation (1) with values from Hazard and Damage factors, the GHG Emission Risk of a territory ranges from 1 to 3, with 1 being a low risk of GHG emissions, 2 being moderate and 3 being a high emission risk from a forest fire. Equation (12) represents the complete GHG emission Risk (GER) model, and Equations (13) and (14) represent the development of the factors into their composing variables.

Equation (15) represents an adaptation of Equation (13) in a region when cartography on Preventive silviculture factors (PS) could be not obtained.

$$GER = H \times D \times EV \quad (12)$$

$$GER = H \times (VAR) \times (0.43FM + 0.36C + 0.15S + 0.06O)/(0.27PS + 0.11PI + 0.61SH) \quad (13)$$

$$GER = FF \times (VCS + SOC) \times (0.43FM + 0.36(Ict \times Ic \times Io) + 0.15S + 0.06O)/(0.27\ ((PB + VT)/2) + 0.11(((FN + RN) + WSN)/2) + 0.61\ (L \times E)) \quad (14)$$

$$GER = FF \times (VCS + SOC) \times (0.43FM + 0.36\ (Ict \times Ic \times Io) + 0.15S + 0.06O)/(0.17\ (((FN + RN) + WSN)/2) + 0.83\ (L \times E)) \quad (15)$$

After applying the final equations (Equations (14) or (15)), the GHG Emission Risk of a territory ranged from 1 to 5, with 1 representing the least risk of GHG emissions and 5 representing the riskiest areas if a fire event occurs. These values were reclassified into three groups to differentiate the zones with low risk, moderate risk and high risk. This classification used the mean ($\bar{x}$) and standard deviation (SD) according to Table A12.

Note that this indicator is only valid for comparing intraregional risk values but not for interregional comparisons. The values from one region are not comparable to another, as the data sources and, consequently, the input data might be different. This GER indicator is useful and helpful in terms of identifying and locating the areas within a territory with a higher GHG emission risk in order to establish them as priority action areas and support decision making at all levels.

2.4. Chelva Forest District as Case Study

The Chelva Forest District is located in the northwestern part of the province of Valencia. It covers 183,497 ha, of which 134,121 ha is forest land. From the total area, 108,608 ha are under public management, 93.8% of which are Public Utility Forests, and the rest is forests under consortium or agreement.

Aleppo pine (*Pinus halepensis*) is the dominant tree species occupying 38.5% of the forest district according to [96]. It was greatly favoured by the reforestation of this area from the 1950s to the 1970s and its high capacity to grow in abandoned fields. Shrubland occupies 36% of the surface. The Chelva forest district falls within the climatic domains of mesomediterranean shrubland (*Bupleuro rigidi-Querceto rotundifoliae sigmetum*) and its degradation stages with the presence of kermes oaks (*Rhamno lycioidi-Querceto cocciferae sigmetum*) [97]. Agricultural land is mainly dominated by almond trees, olive groves, cereals, walnut trees and truffle oaks.

Massive, hard limestone and dolomite outcrop on 67% of the surface, while 21% of the surface outcrops limestone and marl in alternation or limestone and clay in alternation. Soils developed from hard rocks (limestone and dolomite) tend to be very shallow (an effective depth of less than 30 cm), stony and often with few carbonates or completely decarbonated.

Orographically, the region is a very rugged territory (average altitude of 500 metres) with a minimum of 400 m in the extreme south and 1400 m in the northwest, the central axis of which is the course of the Turia river, forming wide valleys. Mountainous reliefs dominate with moderate slopes (15–30%) in 43% of the area, followed by gentle slopes (<15%) in 34% of the area and 18% steep slopes (>30%).

2012 was one of the worst years in terms of forest fires for the Valencian Community. A total of 57,500 forest hectares were affected by 502 fires, 8 of which exceeded 100 ha. The Andilla fire was the second biggest fire in all Valencian communities. It started on 26 June

2012 and was under control seven days later, during which it burned 94% of forest land (approximately 19,688 ha) and 6% of agricultural land (1256).

In addition, other big fires occurred in a part of the same forest district, namely, the Chelva fire (started 1st of June 2012 and burned 670 ha) and the Chulilla fire (23 September 2012, which burned 7096 ha). Figure 2 shows its location within the Chelva forest district.

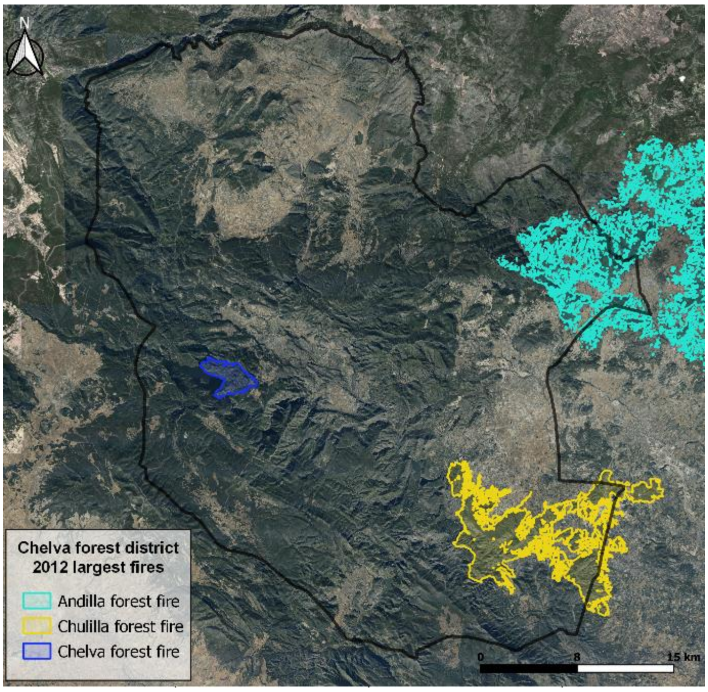


Figure 2. Location of the largest fires in Chelva forest district in 2012.

All the variables were studied and calculated to obtain hazard, emission vulnerability, damage and, finally, GHG emission risk values for *Pinus halepensis* forest lands, as the most representative forest ecosystem. Data sources can be consulted in the Supplementary Material.

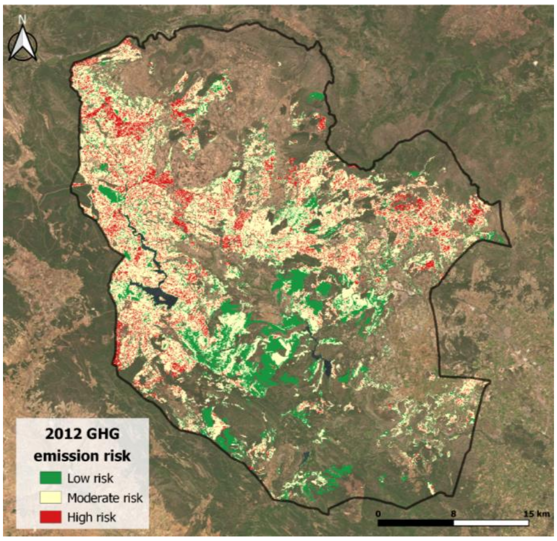
The developed model was applied in the Chelva forest district before the big forest fires occurred in 2012 and in 2020 to assess GHG emission risks. To interpret the resulting values, several scale-ups of the areas affected by big forest fires in 2012 (Andilla fire, Chelva fire and Chulilla fire) were analysed and discussed, and the 2012 emission risk level was compared with the 2020 risk level in the same areas.

3. Results and Discussion

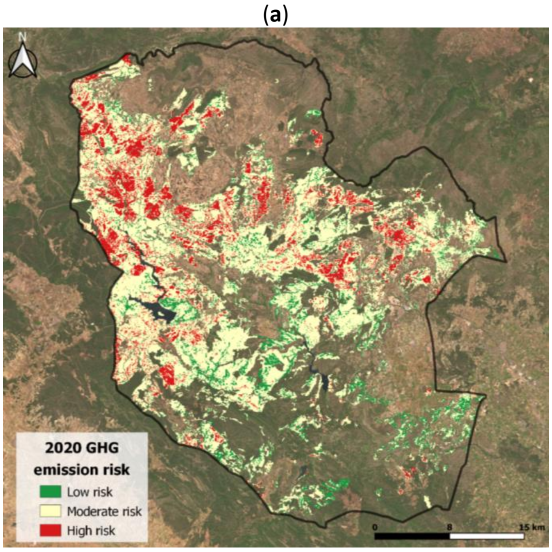
Table A13 shows the average risk values resulting from the application of Equations (13) or (14) to the Valencia study area. Figures 3 and 4 show the resulting GHG emission risk in the Chelva forest district in 2012 and in 2020, respectively.

The results are subscribed to *Pinus halepensis* forest ecosystems. In an overview, it can be observed that GHG emission risk values in 2012 were lower in the central and southern parts of the study area, with higher values distributed mainly in the northeast and northwest. While lower values increased to the moderate emission risk level in these areas, in the Northeast, the emission risk has dropped from high to moderate due to the Andilla fire impacts and the Chelva fire impacts in the Southwest.

The carbon stock loss and consequent fuel model change after the Andilla fire affected the potential fire severity and spatial heterogeneity variables. Moreover, this affected the landscape's potential resistance by increasing fuel discontinuity. This shows that a fire event has a high impact on future emission risk levels when there is no substantial modification of the rest of the influencing factors in the affected areas.



(**a**)



(**b**)

Figure 3. (**a**) GHG emission risk in Chelva forest district in 2012, previous to the fires. (**b**) GHG emission risk in Chelva's forest district in 2020.

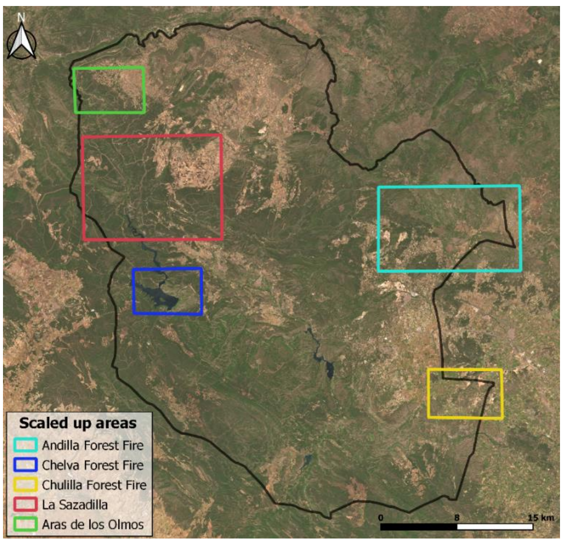


Figure 4. GHG emission risk scale-up areas.

3.1. GHG Emission Risk Cartography

Figure 3a shows the result of the implementation of the GER on *Pinus halepensis* forest ecosystems of the Chelva forest district in Valencia (Spain) in 2012 before the big fire events that took place in June, July and August of 2012 (Andilla, Chelva and Chulilla fires, respectively).

Overlapping pictures 2 and 3a, it can be observed that the upper-right area where the Andilla fire later took place had a marked GHG emission risk, as well as Chelva lake surroundings where the Chelva fire took place (middle-left area). The case of the Chulilla fire area is not so easily observable due to the restricted *Pinus halepensis* forest ecosystems areas in that part (bottom right), but it can be appreciated that medium and high GHG emission risk also prevailed. This indicates that, despite the fire ignition point, the consequent fire spread or real emissions cannot be predicted by the GHG emission risk level. It shows the riskiest areas in terms of GHG emissions in the case of a fire event and how emission risk changes with the modification of model variables' values over time, as can be observed in Figure 3b.

Figure 4 shows other areas that were used to interpret and validate the model results in detail with the scaling up of these areas and their GHG emission risks in 2012 and 2020.

3.1.1. Scale Up of GHG Emission Risk in Andilla Fire Burned Area (2012)

Figure 5a presents more in detail on the Andilla forest fire area previous to the fire in 2012 and its emission risk (Figure 5b), while Figure 5c shows the more recent state of risk (2020).

It can be observed that the areas with higher biomass density (Figure 6a) and therefore carbon stock together with steeper and higher continuous landscape areas showed high GHG emission risk values, while roads and firebreaks reduced this risk.

Later, in the 2020s, as can be observed in Figure 6c, the relative GHG emission risk decreased in the burned areas while it was maintained or increased in those that remained unburned. This may be due to the decrease in carbon stock, a change in fuel model types after the fire and the lower continuity of fuels in the burned area. In the case of the unburned areas, carbon stocks have increased during these ten years and have reached more emissive stages in the fuel models.

3.1.2. Scape Up of GHG Emission Risk in the Burned Area by Chelva Fire (2012)

Figure 6a shows the orthophoto image for 2010 before the Chelva fire (2012) and Figure 6b presents the GHG emission risk assigned for that area at that time, before the fire event.

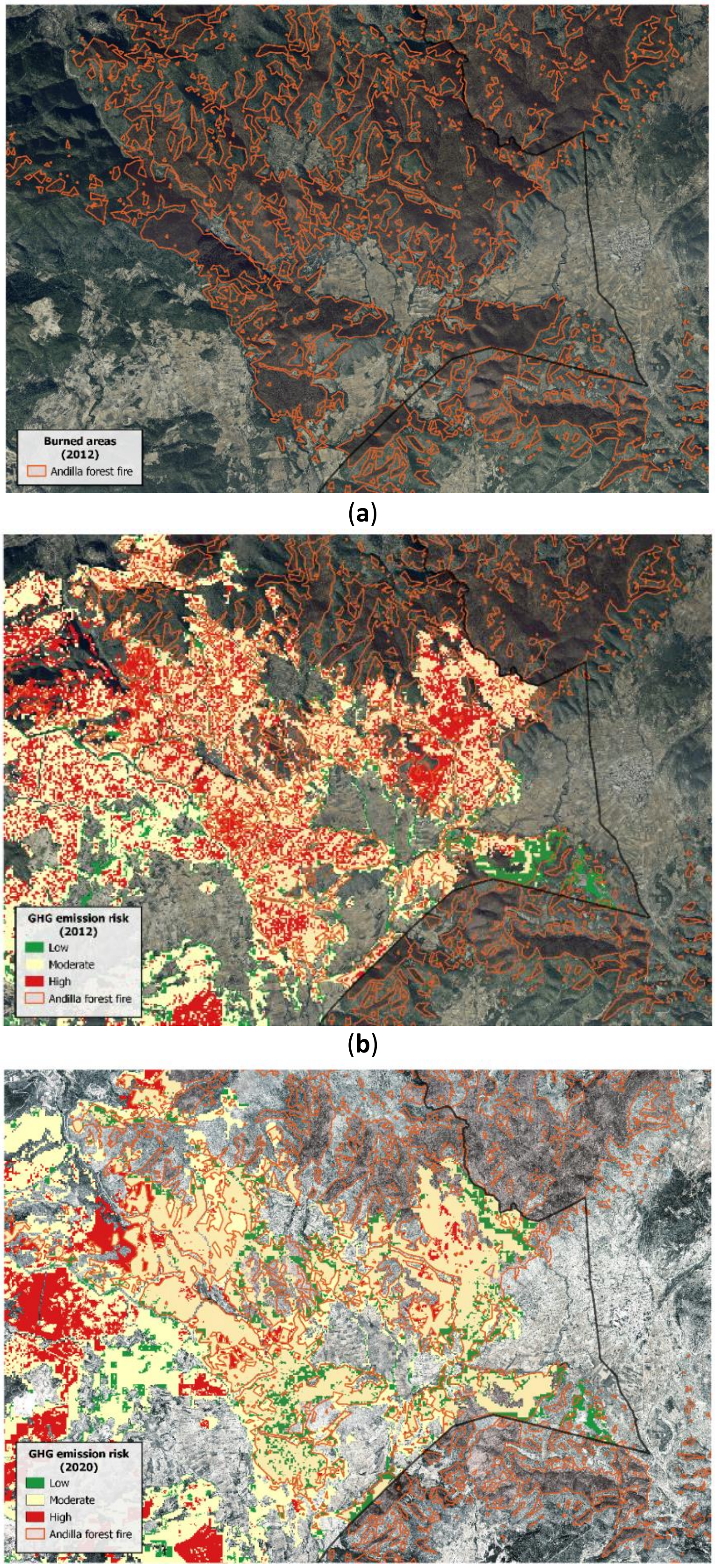
The Northeast area with a higher emission risk was burned by the Chelva fire. Again, it can be observed that areas with an apparent higher amount of biomass had higher emission risks and preventive infrastructure such as the firebreak was decreasing the risk of the area.

In 2020, GHG emissions risk is shown in Figure 6c. It can be observed that the burned areas have decreased their emission risks.

3.1.3. Scale Up of GHG Emission Risk in Chulilla Fire Burned Area (2012)

Figure 7a shows the orthophoto image for 2010 before the Chulilla fire (2012) and Figure 7b shows the emission risk assigned for that area before the fire event.

Using Figure 7b,c to compare the GER results, it can be observed that the Chulilla-fire-burned area reduced the carbon stock. Moreover, the decrease in GHG emission risk was due to a change in spatial heterogeneity because of the higher diversity of soil land use than in 2020.



(c)

Figure 5. (**a**) Scale up of Andilla forest fire (2010 orthophoto). (**b**) GHG emission risk in 2012. (**c**) GHG emission risk in 2020 (2020 orthophoto).

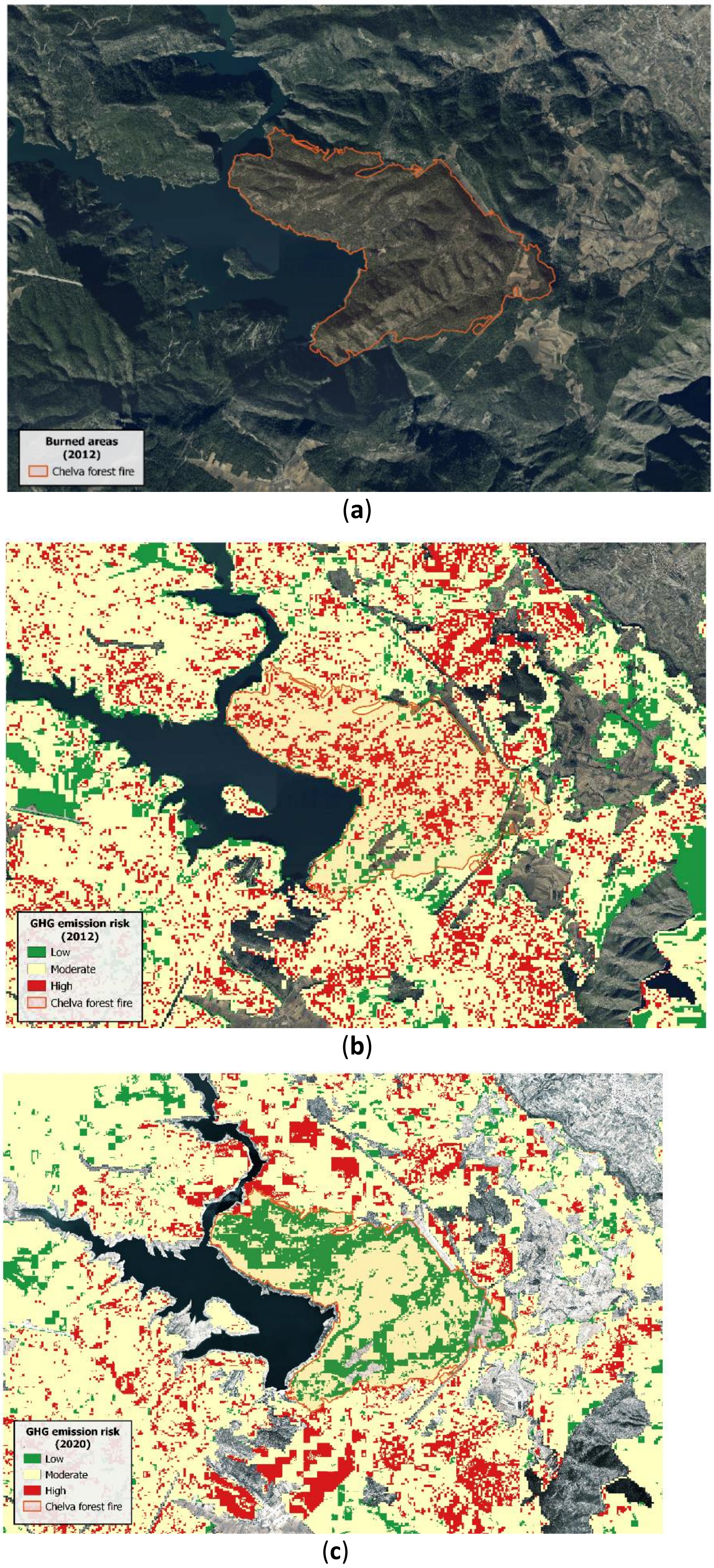


Figure 6. (**a**) Scaling up of Chelva forest fire (2010 orthophoto). (**b**) GHG emission risk in 2012. (**c**) GHG emission risk in 2020.

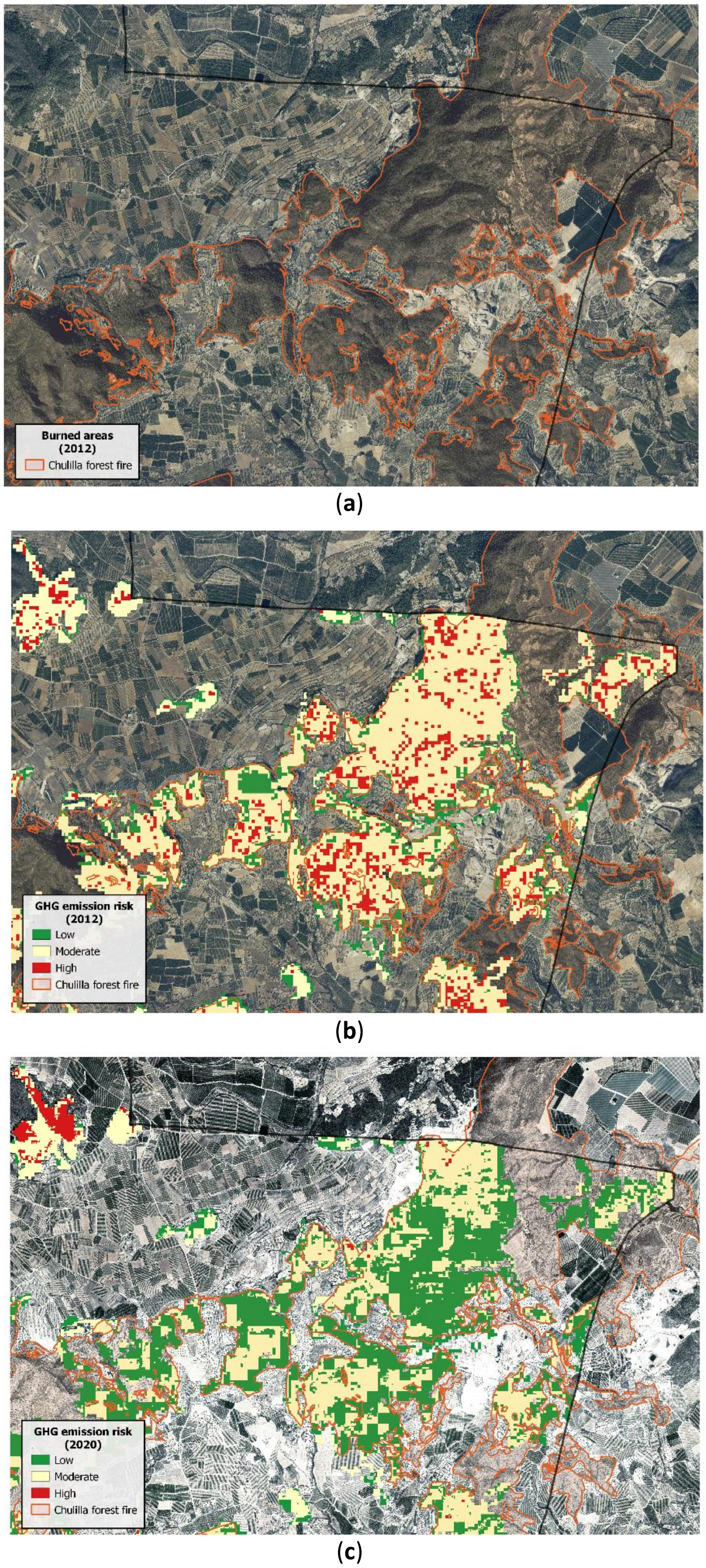


Figure 7. (**a**) Scale-up of Chulilla forest fire (2010 orthophoto). (**b**) GHG emission risk in 2012. (**c**) GHG emission risk in 2020.

3.1.4. Scale Up of GHG Emission Risk in La Sazadilla

Figure 8a shows the orthophoto image for 2010 in the surroundings of La *Sazadilla* and Figure 8b presents the GHG emission risk assigned for that area. In the centre of Figure 8a, a high accumulation of carbon can be appreciated in forest ecosystems. Figure 8b shows that this area did not exhibit a high risk as it is diminished by the influence of water points for firefighting that create a risk reduction buffer around them (appreciable as a crown in Figure 8b in the bottom-right corner and the centre of the figure). Moreover, an extended low-risk area (green area) of young forest stands can be observed with relatively low carbon stocks. Forest heterogeneity and discontinuity can be also observed in the centre bottom area.

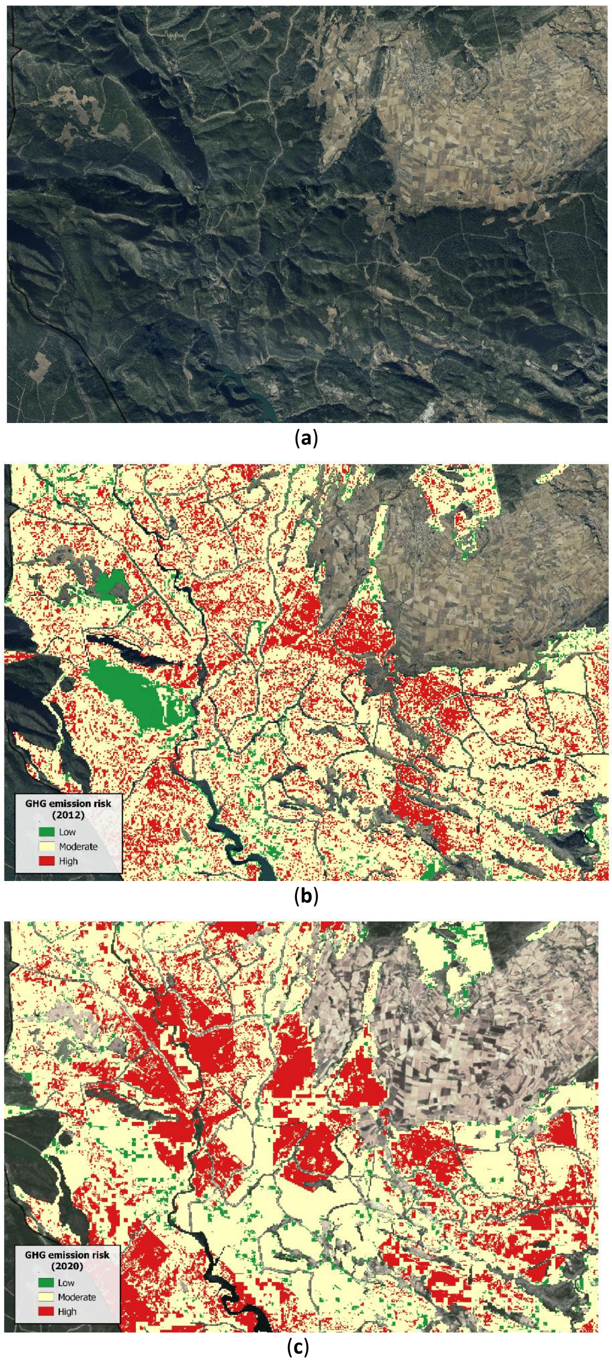


Figure 8. (**a**) Scale-up of La Sazadilla (orthophoto 2010). (**b**) GHG emission risk in 2012. (**c**) GHG emission risk in 2020.

Nevertheless, Figure 8c, which is the most recent GHG emission risk map, shows a decrease in the reduction effect of the water point due to the increase in carbon stock, with the rest of the variables' values being equal after ten years. Higher-risk fuel model types influenced this general increase in GHG emission risk in this area.

3.1.5. Scale Up of GHG Emission Risk in Aras de los Olmos

Again, Figure 9a shows the orthophoto image for 2010 in the surroundings of Aras de los Olmos and Figure 9b presents the emission risk assigned for that area at that time.

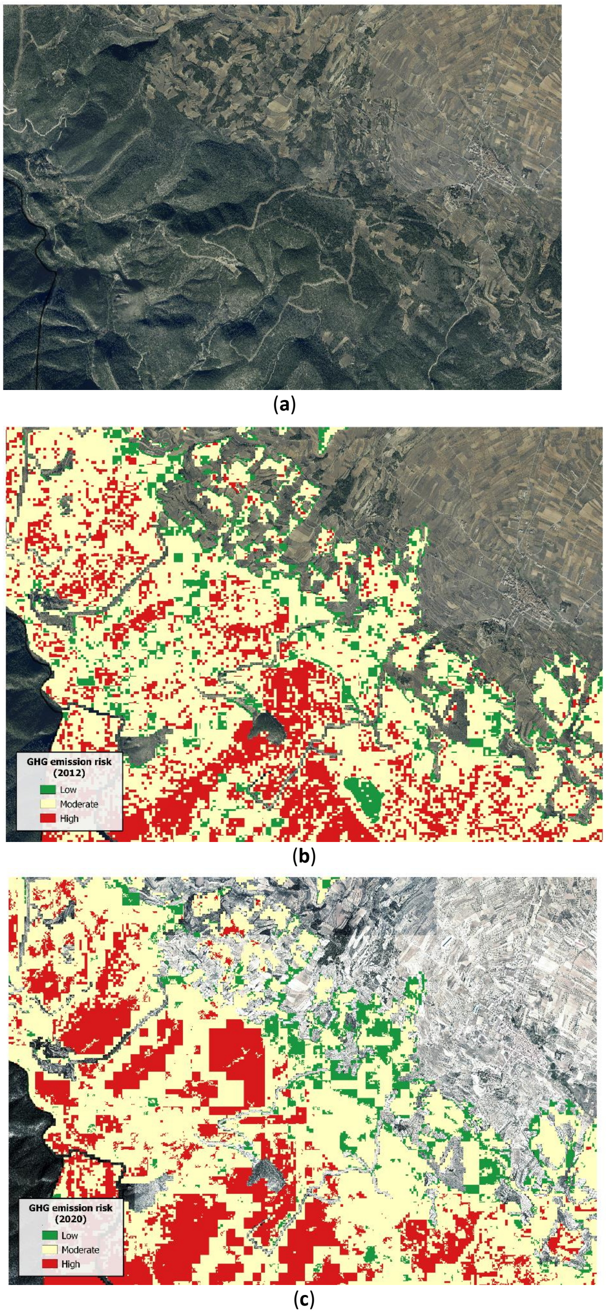


Figure 9. (**a**) Scale-up of Aras de los Olmos (orthophoto 2010). (**b**) GHG emission risk in 2012. (**c**) GHG emission risk in 2020.

A general increase in risk can be observed between 2012 (Figure 9b) and 2020 (Figure 9c). This is due to the increase in carbon stock, fuel model change and spatial heterogeneity reduction due to the increase in the abandonment of agricultural terraces.

3.2. Framework, Restrictions and Future Research Envisaged

This model has been developed with the objective of providing an assessment of priority areas for strategic long-term planning to support decision making for preventing high emissions in the atmosphere from forest fires.

The GHG emission risk of a landscape or region is the relative value of a determined region that cannot be compared with other regions in terms of the amount of emission as it indicates an intrinsic regional risk level according to regional conditions and data availability.

Taking this into consideration, there are many variables affecting the risk of emissions that could not be included in the developed model as there are no regional cartographies of these variables or they need to be elaborated on; for instance, updated fuel models or preventive silviculture (not only treated areas but also treatment intensity). On the other hand, the quantification of carbon stocks highly depends on the data available, and National Forest Inventories (NFI) are too time spaced (more than 16 years have already passed since the last NFI in the Valencian Community) to rely on them. Therefore, new approaches such as remote sensing quantification of lidar need to be used to update data on carbon dynamics.

The potential fire severity is a dynamic variable that highly affects the GHG release by a fire and is highly dependent on the meteorological window (temperature, humidity and wind). It has not been contemplated in the scope of the present development and would need to be included for more tactical planning or firefighting use of the model.

On the other hand, this model has been restricted to the assessment of forest ecosystems without including a very important part of the landscape affecting fire behaviour, which is agricultural lands. Therefore, this model should be extended to all territories in a region in order to obtain more consistent results.

Deeper knowledge of the contribution of ecosystemic, landscape, climatological and fire behaviour variables in terms of emissions is needed to improve the results obtained by the present research. Climatic projections should be integrated into the model for envisaged future assessments and meteorology for operative risk level forecasting.

4. Conclusions

A novel methodology has been developed as a basis for the qualitative spatial assessment of forest fire GHG emissions risk. It provides three levels of GHG emissions risk (low, moderate and high) adapted to intrinsic regional conditions. Moderate- and high-emission-risk areas can be considered hotspots to focus forest fire preventive measures to highly reduce emissions in the case of a forest fire event.

This model has been implemented in the Chelva forest district in the Valencia Region (Spain) as a pilot case for 2012 and 2020. The results show high correspondence between a high emission risk level and the areas burned by big fires in 2012.

It provides a spatial assessment of hotspots of GHG emissions risk to implement an action protocol for reducing GHG emissions risk in the framework of the REMAS project for decision-making.

A detailed sensitivity analysis at the regional level allowed us to observe and quantify the effects of forest and landscape management on variables such as carbon stock, fuel models, preventive silviculture, preventive infrastructure and landscape spatial heterogeneity that affect potential fire severity and potential fire resistance and therefore are able to reduce the emission risk level in a region. This is key information for decision making and can be provided by the present model.

The inclusion and consideration of GHG forest fire emission risk in strategic and tactical regional risk and forest planning is a milestone aligned with the latest international objectives and commitments to emission reductions that will not only prevent high releases of GHG emissions but also increase resilience and reduce fire severity linked to megafire events. Moreover, this model contributes to measuring the objectives of the European

Commission for 2035 [29] of reducing the risks for forests in a context of uncertainty due to climate change.

Being aware of the vulnerability of carbon stocks in forest ecosystems and the enormous natural capital of rural communities and the value at risk that represent the case of a forest fire event is the first step in holistic and consistent climate change mitigation action that not only considers anthropic GHG sources, but also possible GHG emissions caused by forest fires that can be actively prevented, managed and reduced.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fire6010008/s1.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Fire frequency assigned values [84].

Fire Frequency (F_i)	Rating	Value
<0.2	Very low	0.8
0.2–0.49	Low	0.9
0.5–1.99	Moderate	1
2–3.99	High	1.1
4–5.99	Severe	1.2
>6	Extreme	1.3

Table A2. Vegetation and soil carbon stock assigned values for the Value at Risk rating.

VAR (Mg C/ha)	Value
0–20	1
21–40	2
41–60	3
60–80	4
>80	5

Table A3. Preventive silviculture and infrastructure factors' assigned values.

PS	Value
Non-existent	0
Existent	1

Table A4. Landscape assigned values.

Shannon-Wiener Index (H′)	Rating (Heterogeneity)	Value
0–1	Very low	5/5
1–2	Low	4/5
2–3	Moderate	3/5
3–4	High	2/5
4–5	Very high	1/5

Table A5. Ecosystem assigned values.

Shannon-Wiener Index (H′)	Rating (Continuity)	Value
0–20	Very high	1/5
20–40	High	2/5
40–60	Moderate	3/5
60–80	Low	4/5
80–100	Very low	5/5

Table A6. Vegetation index assigned values.

FM [83]	Value	FM [98]	Value
TL1-TL4	1/10	1, 2, 8	1/5
TU1, TL5, TL7, SH1	2/10		
GR1, GS1, SH2, SH3	3/10	5, 6	2/5
GR2, GR3, GS2, SH4	4/10		
GS3, SH6, SH8, GR4	5/10	3, 7, 9	3/5
GR5, GR6, TU2, TL6	6/10		
SB1, SH7, TL8, GS4	7/10	10, 11	4/5
TU3, TU4, TL9, SB2	8/10		
SH5, SB3, SB4, TU5	9/10	4, 12, 13	5/5
SH9, GR7-GR9	10/10		

Table A7. Thermicity Index for Mediterraneas cases assigned values [85].

Thermicity index (Itc)		Thermotype	Value
Itc > 120	Itc < 120, Tp [1]		
-	1–190	Upper Cryoromediterranean	1/12
-	191–450	Lower Cryoromediterranean	2/12
-	451–675	Upper Oromediterranean	3/12
-	676–900	Lower Oromediterranean	4/12
120–150	901–1200	Upper Supramediterranean	5/12

Table A7. *Cont.*

Thermicity index (Itc) Itc > 120	Itc < 120, Tp [1]	Thermotype	Value
150–220	1201–1500	Lower Supramediterranean	6/12
220–285	1501–1825	Upper Mesomediterranean	7/12
285–350	1826–2150	Lower Mesomediterranean	8/12
350–400	2151–2300	Upper Termomediterranean	9/12
400–450	2301–2450	Lower Termomediterranean	10/12
450–515	2451–2650	Upper Inframediterranean	11/12
515–580	>2650	Lower Inframediterranean	12/12

[1] At any latitude, when the thermic index (Itc) is less than 120, or when the continental index (Ic) is equal to or greater than 21, the value of the annual positive temperature (Tp) is used to calculate the thermotype which represents the sum in tenths of degrees centigrade of the monthly mean temperatures (Ti) of the months with an average temperature above 0 °C (Tp = sum of Ti> = 0°).

Table A8. Thermicity Index for Temperate cases assigned values [85].

Thermicity Index (Itc) Itc > 120	Itc < 120	Thermotype	Value
-	1–190	Upper Cryorotemperate	1/11
-	191–380	Lower Cryorotemperate	2/11
-	381–590	Upper Orotemperate	3/11
-	591–800	Lower Orotemperate	4/11
-	801–1100	Upper Supratemperate	5/11
120–190	1101–1400	Lower Supratemperate	6/11
190–240	1401–1700	Upper Mesotemperate	7/11
240–290	1701–2000	Lower Mesotemperate	8/11
290–350	2001–2175	Upper Termotemperate	9/11
350–410	2176–2350	Lower Termotemperate	10/11
>410	>2351	Infra Template	11/11

Table A9. Continentality Index assigned values [85].

Continentality Index (Ic)	Continentality Types		Value
0–10	Oceanic	Hyperoceanic	1/6
10–15		Euoceanic	2/6
15–21		Semioceanic	3/6
21–27	Continental	Semicontinental	4/6
27–46		Eucontinental	5/6
46–65		Hypercontinental	6/6

Table A10. Ombrothermic Index assigned values [85].

Ombrothermic Index (Io)	Rating		Value
<0.1	Ultrahyperarid	Ultrahyperarid	16/16
0.1–0.2	Hyper arid	Lower hyper arid	15/16
0.2–0.3		Upper hyper arid	14/16
0.3–0.6	Arid	Lower arid	13/16
0.6–1.0		Upper arid	12/16
1.0–1.5	Semi-arid	Lower semi-arid	11/16
1.5–2.0		Upper semi-arid	10/16
2.0–2.8	Dry	Lower dry	9/16
2.8–3.6		Upper dry	8/16

Table A10. *Cont.*

Ombrothermic Index (Io)	Rating		Value
3.6–4.8	Subhumid	Lower subhumid	7/16
4.8–6.0		Upper subhumid	6/16
6.0–9.0	Damp	Lower damp	5/16
9.0–12.0		Upper damp	4/16
12.0–18.0	Hyperhumid	Lower hyperhumid	3/16
18.0–24.0		Upper hyperhumid	2/16
>24.0	Ultrahyperhumid	Ultrahyperhumid	1/16

Table A11. Slope assigned values.

Slope Range	Value
0.0–15.3%	1/4
15.3–26.4%	2/4
26.4–39.7%	3/4
>35.7%	4/4

Table A12. Orientation assigned values.

Orientation Range	Rating	Value
Flat areas	-	1/4
315–45°	N	1/4
45–135°	E	2/4
225–315°	W	3/4
135–225°	S	4/4

Table A13. GHG Emission Risk assigned values.

Range	Rating	Value
$0 - (\bar{x} - SD)$	Low risk	1
$(\bar{x} - SD) - \left(\bar{x} + 1SD\right)$	Moderate risk	2
$(\bar{x} + SD) - 5$	High risk	3

Appendix B

In this appendix the methodology for rating fuel model risk is described. This methodology has been provided by fire analysts from VAERSA (public company dependent on the Conselleria d'Agricultura, Desenvolupament Rural, Emergència Climàtica i Transició Ecològica from Valencian Government, Generalitat Valenciana).

The methodology consists of comparing the different fuel models' fire behaviour characteristics in order to assess the inherent danger of each of them. "BehavePlus (5.0.5)" software has been used for simulating fire severity of each fuel model category.

Concrete framework conditions have been established according to most common large forest fires standard conditions in Valencian Region for the simulations: Fuel Moisture 1 h = 3; 10 h = 5; 100 h = 7; Live Herbaceous = 70; Live Woody = 30.

These conditions have been applied to different fuel models, concretely [83,98], classifications.

For the simulation, slope steepness and wind speed variables will vary, establishing 4 scenarios:

- plain surface and 30 km/h of wind speed (1);
- plain surface and 50 km/h of wind speed (2);
- 30% of terrain slope and 30 km/h of wind speed (3);

- 50% of terrain slope and 50 km/h of wind speed (4).

Additionally, simulations have been run for both, sheltered and unsheltered forests. When simulating sheltered forest types, overstory conditions were: 70% of canopy cover and 12 m of canopy height 1 m of canopy base height (typical conditions for Pinus halepensis species-Valencia's regional case), and 0.2 kg/m^3 of canopy bulk density for *Pinus halepensis* according to [99,100]. With all these conditions and scenarios, surface forest fires have been simulated.

To assess the danger of a fuel model and to compare it among them, the most interesting parameter is the fireline intensity. According to [101], fireline intensity is defined as the heat energy release per unit time from a one-foot (one-meter) wide section of the fuel bed extending from the front to the rear of the flaming zone. This variable is a function of rate of spread and heat per unit area and is directly related to flame length. Consequently, it represents the potential biomass quantity that is susceptible to be combusted.

In case that the critical surface flame length value is overcome in a simulation, it is supposed that the fire will make a transition to the crowns. If that situation occurs, the heat generated by the crown combustion is added to the heat per unit area to calculate the total fireline intensity. If not, only heat per unit area has been considered.

Finally, the fireline intensity values for both Rothermel and Scott and Burgan have been divided into five and ten percentiles, respectively. According to these percentiles, the risk or danger has been ranged from 1 to 5, being all the fuel models included in percentile 20 or percentile 10 classified as lowest risk, for [83,98] classifications, respectively.

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