Environmental Sciences Proceedings

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Modernized Forest Fire Risk Assessment model based on the case study of three Portuguese Municipalities frequently affected by forest fires†

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† Presented at the 1st International Electronic Conference on Forests, 15–30 November 2020; Available online: https://sciforum.net/conference/IECF2020

Published: 07 November 2020

Abstract: The number of forest fires ignitions has decreased worldwide, thus observing increased levels of intensity and destruction, endangering urban areas, and causing material damages and deaths (Portugal - 2017). Forest fire hazard mapping supported by the surveillance strategy targeted at very susceptible areas with high losses' potential are the common tools to fire prevention. Each Municipality creates its own Forest Fire hazard map, and so it is observed that along the administrative boundary's discrepancies occur, even when identical types of landuse are in place. With the evolution of geographic information systems technology sustained by the open-source satellite imagery, along with the innovative Habitat Risk Assessment model of the InVEST software allowed the creation of an easily applicable trans-administrative boundary fire hazard map, with frequent update capabilities and fully open source. This work considered three Municipalities (Tomar, Ourém, and Ferreira do Zêzere) which annually observe various forest fire occurrences. Results enabled a homogeneous Forest Fire Risk Map creation, using landuse, slope, road access network, fire ignitions' history, visualization basins, and the Normalized Difference Vegetation Index (NDVI) as variables. All variables correlate with each other using different weights, in which the different classes of landuse are considered as habitats and the remaining variables as fire hazard stressors. The results produce a coherent monthly updated Risk Map, which is an alternative to many risk assessment systems used worldwide.

Keywords: Fire Hazard; InVEST; NDVI; Model; Forest Fires

1. Introduction

Wildfires arise naturally from sources such as spontaneous combustion of dry matter, under high temperatures and wind conditions or most commonly lightning strikes [1]. Most frequently wildfire ignitions arise as accidental consequences of human practices, though many have been proven to be criminal or negligent actions [2,3].

Mediterranean forests are regularly subjected to a large number of fires [4–6], changes in land use patterns [7] and the impacts of socio-economic factors on land management practices [8], further aggravated by major modifications to forest ecosystems during the second half of the 20th century [9] along with forest modification by fire recurrence [10] contributed towards wildfire intensification.

With farmland abandonment and forest modification trends, fire concentration is becoming rather predominant in Southern European regions [4]. The past years (2018–2019) fires in Europe observed over 800,000 hectares of burnt areas in Portugal, Italy and Spain alone [11]. The number of occurrences regarding forest fires has decreased worldwide [12], thus observing increased levels of intensity and destruction, which in many cases endanger urban areas causing not only material damage but also deaths as those occurred in Portugal in 2017 [9]. Wildfires, and in particular forest fires, are increasing in intensity reaching catastrophic dimensions, as a result of poor forest management, territorial planning and economic pressures, also driven by aggravated climate change conditions [7,10,13].

Surely fire represents an important ecological function and a strategic agricultural tool to fertilize soils [14,15], however the fire-fighting associated costs, the human lives [16], the property and natural resources loss [11], the environmental greenhouse gas emissions and atmospheric pollution factors [17] and the ecosystem services lost [15] represent heavy counter-weighs of sustainability scales.

Wildfires can be termed as forest fires, grass fires, peat fires, and bush fires depending on the predominant type of vegetation that is being burnt. Forest fires in Portugal, as in the Mediterranean region, can occur at any given time, however they are more prevalent during the dry season between the beginning of summer and the start of the winter rains [18,19]. Climate change effects, increasing drought frequency and associated average temperature rise, when combined with population density and economic activity which increase the urban forest interface, will further increase wildfire frequency and severity [8,9]. All catastrophic fires in Portugal occur within the summer period, when the association of 3 variables: heat wind and lack of humidity, the 30's rule: over 30 km/h winds, over 30 °Celsius and less than 30% humidity.

The evolution of geographic information systems (GIS) with a panoply of software and applications, both commercial and open source enables easy fire-risk cartography, which requires dynamic process since a certain location in a given time quickly changes either by seasonal changes, land occupation or land use, thus fundamental tool in support of forest fire prevention, surveillance and mitigation [20,21]. Wildfire mitigation analysis evolved considerably since the turn of the century, satellite imagery and remote sensing (RS) analysis are now widely used to detect, monitor the behaviour, aid operational fire-fighting activities, and facilitate the mapping of burned areas. These technologies proven to be more efficient and precise than traditional surveying methods, reducing risk, burnt areas, and saving human lives [21].

By using models, maps, and databases in geospatial analysis of fire variables, every country prone to wildfires produces risk maps as a strategy to optimise monitoring and minimise losses during the seasonal fire-fighting season. Risk mapping focuses on low-probability, high-consequence adverse events that are stochastic in space. As an operational result, countries allocate watchtowers, open forest accessibility facilities, distribute facilities and surveying mobile teams in risky areas [16].

The Portuguese municipality risk map (PMDFCI) production guidelines proposed by the governmental Institute for Nature Conservation and forestry (ICNF) contemplates Hazard as a multiplication product of probability and Susceptibility and Potential losses as a multiplicative product of Vulnerability and Economic Value, where Risk is the multiplicative result of Hazard and Potential damage (Figure 1).

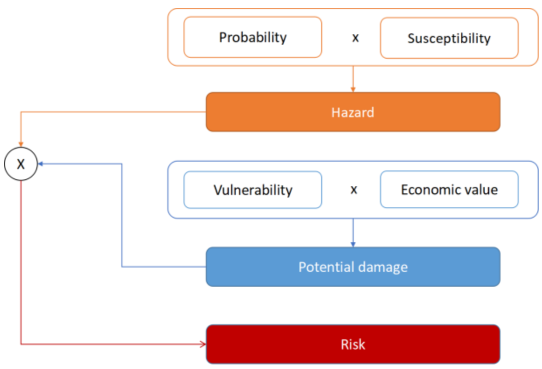

Figure 1. PMDFCI production instructions (Source ICNF).

The Probability criteria considers fire history as the product of occurrences multiplied by 100, divided by the number of series (years), whereas Susceptibility considers land-cover in eight categories with forest and brush with higher susceptibility and slope, where steeper slopes are considered most susceptible. Vulnerability criteria is applied to combustion resilience of materials and economic market value of goods.

Some of the underlying problems observed with PMDFCI methodology concern the individually implemented municipality base risk maps which create hard boundaries where same habitat across two municipalities observes different risk class. Furthermore, the model is mostly produced with static characteristics where slow update variables are used (Figure 2).

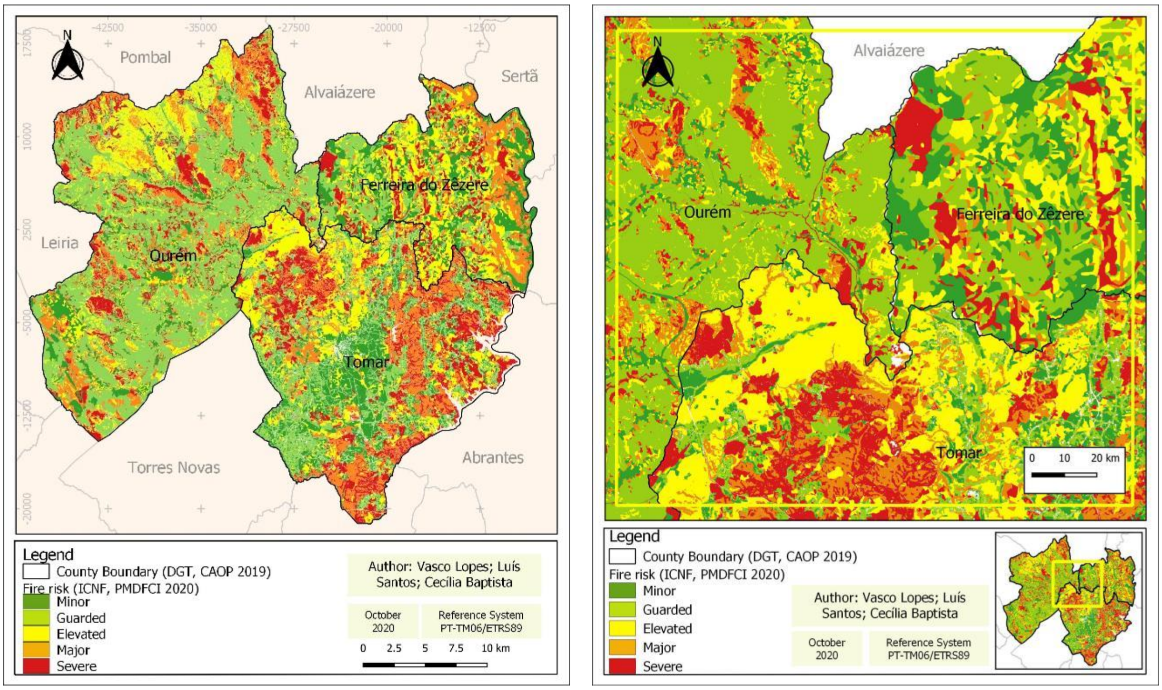

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Figure 2. a) PMDFCI risk model for the study region, b) PMDFCI Risk detail of Municipality boundaries.

The objective of this paper is to produce an open source, updatable and upgradable, transboundary base solution of forest fire ignition risk mapping and use it for identifying locations, determined from a set of slow and dynamic variables, thus mitigating susceptibility and social/infrastructural vulnerability.

2. Materials and Methods

With the evolution of geographic information technology and the multitude of free satellite imagery, the methodology used in the Habitat Risk Assessment model, one of the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) models used to map and value the goods and services from nature that sustain and fulfil human life. The InVEST Habitat and Species Risk Assessment (HRA) model allows the assessment of cumulative risk posed to habitats by human activities, delivering ecosystem risk map, risk maps for each individual habitat, resulting from the contribution of exposure and consequence to overall risk [22].

This work enabled the creation of a Fire Ignition Risk map, homogeneous which used as variables land occupation, slope, forest road network, history of fire ignitions, visualization basins and the Normalized Difference Vegetation Index (NDVI). All variables correlated with each other using different weights, in which the different classes of land occupation enter as habitats and the remaining as stressors for the problem of fires.

2.1. Study Area

The study region located in the centre of Portugal covering the transition between the Tagus river floodplains and the Montejunto-Estrela mountain range (Central Portugal; Figure 1). Administratively the region comprises the municipalities of Tomar, Ourém and Ferreira do Zêzere belonging to Santarém district, Nomenclature of Territorial Units for Statistical Purposes (NUTS) level II and III, the municipalities are inserted in the Central region and in the sub-region of the Middle Tagus. Situated in the Mediterranean pluvioseasonal oceanic bio-climatic region [23] with average altitude ranging from 30 to 650m s a l., mean annual precipitation of 66 mm, and a mean annual temperature of 14 °C. This region observes on average 2–3 months of summer drought where wildfires are frequent, particularly because of the association to the poor management, the land abandonment as a consequence of ageing population and desertification, and the choice of species influenced by economic yields.

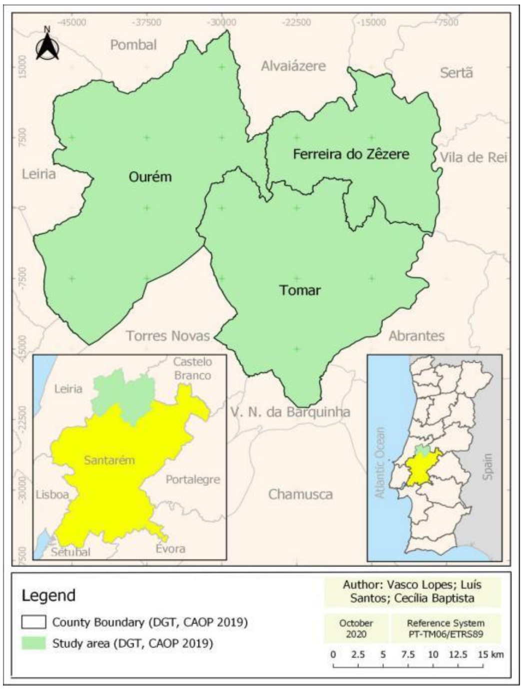

Figure 3. Geographical location of study region.

The region was once prosperous with *Pinus pinaster* plantations speckled with olive orchards and lowland agriculture, nowadays a mosaic of *Eucalyptus globulus* plantations, remnants of *Pinus pinaster*, and shrubland dominated by *Ulex spp*., *Erica Spp*., *Pistacea sp*., *Myrtus sp*. and *Rubus spp*., where once was agriculture, confirming a trend that is further observed as we move north-eastwards. According to the data of the Official Administrative Chart of Portugal (DGT-2019), the three municipalities cover an area of approximately 95,823 ha, divided as follows: Tomar (35120 ha), Ourém (41666 ha) and Ferreira do Zêzere (19037 ha).

2.2. Methods

The methodology applied for the current study used imagery from the satellite constellation Sentinel-2 multispectral instrument (MSI) offered the possibility of obtaining information in medium and high spatial resolution (10–20 m) In particular, the MSI sensor provides spectral information in different bands, allowing for the calculation of pre-fire vegetation greenness, the normalized difference vegetation index (NDVI, Theorem 1). For greenness chlorophyll concentration NDVI we used Red and NIR according to the formula described on Theorem 1.

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

Theorem 1. *Normalized difference vegetation index (NDVI), red region (Red: 650-680nm, 10m resolution) being the near infrared (NIR: 785-899nm, 10m resolution).*

The downloaded images for the study region, level 2A, atmospherically, radiometrically and geometrically corrected, from the 24th of July and 23rd of August 2019 without the presence of clouds were the final data was selected for values up to 0,4, considering loss of chlorophyll as the dynamic variable with monthly images frequency [21,24,25].

The Modernized Dynamic Ignition Risk (MDIR) model (Figure 4) considers ignition risk as the trigger to fire occurrence, both large and small, this factor conveys a safer approach to monitoring and mitigation actions of firefighting agents. The slow geodatabase variables used were land-cover with forest and brush representing higher risk and anthropic territories such as cities lower from National Landcover Maps Level 1 (COS). Road network selected 20m high risk, considering most ignitions start within the proximity of roads, thus emphasizing the criminal and accidental majority of ignitions from National Institute for Nature conservation and forestry (ICNF) [26]. The historical of fire ignitions, considering that a burnt area will, according to natural regeneration, have some years before recurrent ignition, ecological succession will represent higher risk, data used 2011-2019 from the National Service for Nature and Environment Protection (SEPNA). Population density (people per sq. km) according to census 2011 where areas bellow 250 residents increase the risk, desertification, and aged population, from the National Statistics Institute (INE). Slope, considered low slopes as prone areas for ignition, this may cause confusion as high slopes are favourable to fire propagation, however ignition data from the past 9 years reveals that the majority of ignitions occur in lower slope areas, slope was calculated with QGIS from DTM 25m resolution. Visualization through the construction of watchtowers is one of the monitoring strategies implemented worldwide, for this study all areas not visible by at least 3 towers are considered as of high risk, visualization was calculated using the watchtower locations, in turn applied viewshed analysis QGIS plug-in (SEPNA).

The MDIR model adopts free open source software QGIS and GRASS to prepare all vector and raster inputs for the InVEST HRA, applying Landcover as the current habitat split into individual categories, whilst slope, visibility, roads, fire ignition history and population density as stressors. Requiring a classification criteria table, HRA, classifies each variable as exposure or consequence, the habitats will be rated for growth rate, rotation, connectivity, and natural recovery time based on literature information, evaluating data quality and weight. For each stressor ratings were considered for, distribution frequency, change in classification, management efficiency and neighbourhood, also evaluating data quality and weight.

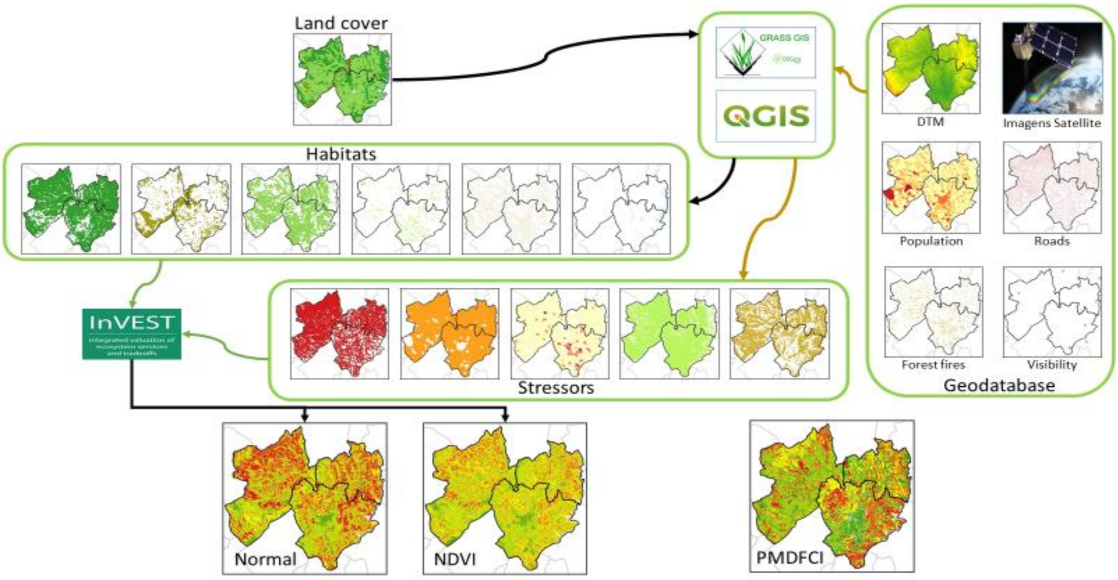

Figure 4. Modernized Dynamic Ignition Risk model (MDIR), elaboration process.

The InVEST HRA model cumulatively analyses habitat characteristics as mitigation factors and stressors as deteriorating factor of risk producing risk maps for the study region.

3. Results and Discussion

Results delivered as risk maps from the HRA for the study region were tested using the different sets of stressors to understand the differences between slow and dynamic variables. As a first run of the HRA, only slow variables were analysed and risk classes attributed as Minor, Guarded, Elevated and Severe, designated Modernised Ignition Risk (MIR), (Figure 5a). Classification considers risk is always present except for water surfaces, and therefore no risk classification was not used in the risk map.

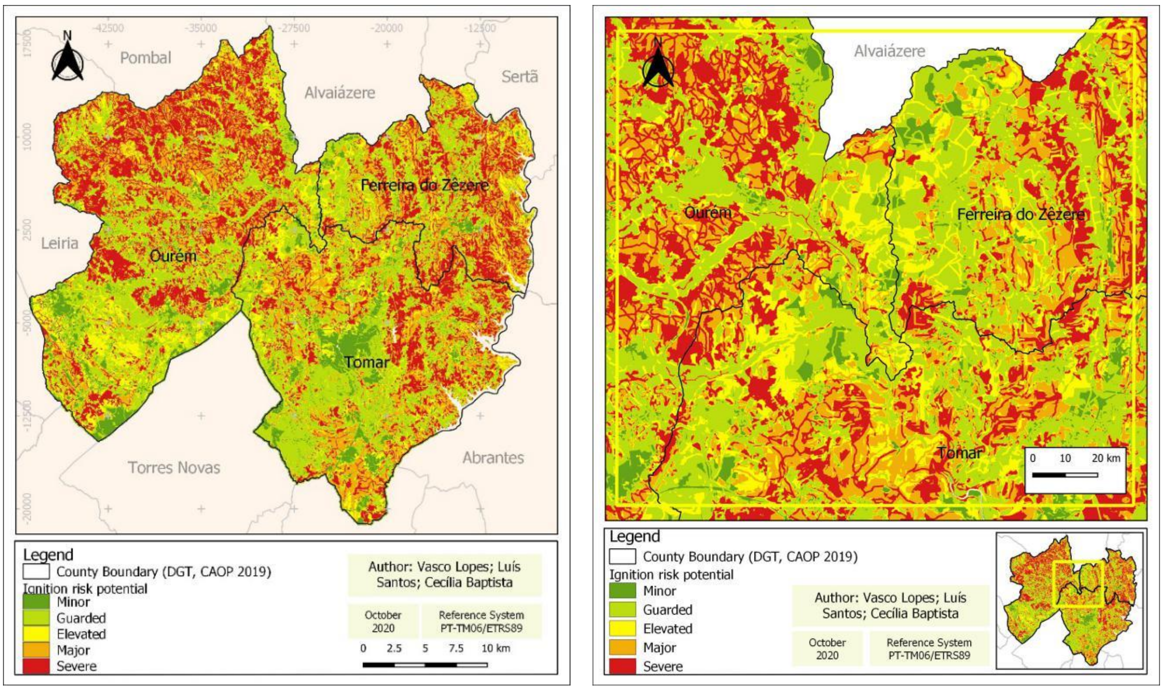

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Figure 5. Ignition Risk Model (MIR) map considering slow variables a) MIR for the entire region, b) MIR detail of inter municipality boundaries.

Results generated from the InVEST HRA in the production of MIR map (Figure 5a) are considerably different from the PMDFCI, when we focus on municipal boundaries, a soft transboundary risk classification can be observed (Figure 5b).

The inclusion of the dynamic (monthly) greenness (NDVI) stress, denominated Modernized Dynamic Ignition Risk model (MDIR), delivers a substantially different ignition risk map (Figure 6 a,b).

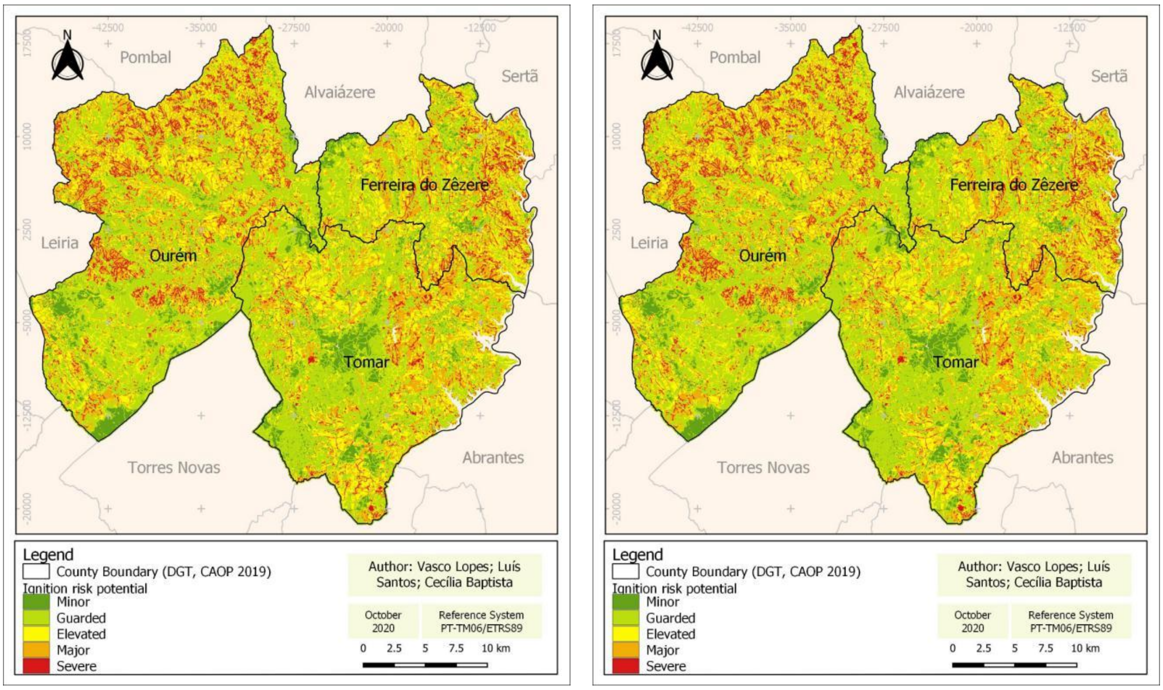

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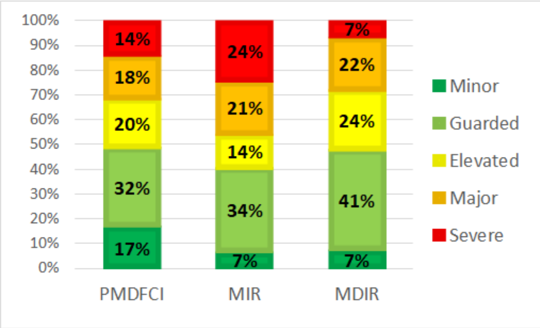
Figure 6. Ignition risk map with slow variables using dynamic NDVI as a stressor, a) NDVI - 24th of July 2019, b) NDVI - 23rd August 2019.

When comparing MIR and MDIR model results with the PMDFCI it is clearly visible the 10% increase of severe risk class in MIR and the 7% decrease in MDIR (Figure 7a), being the former based on slow variables, one can just attribute the latter reduction to the dynamic NDVI stress which re percusses the climatic influence, thus pinpointing severe risk areas. This fact may reveal to be an interesting cue to monitoring and surveying strategies.

On the other hand, lower classifications minor and guarded, when added are 49% for PMDFCI, 48% for MDIR and 41% for MIR. The close percentage observed between PMDFCI and MDIR indicates that natural conditions are equally considered in both models, further evidenced in the geographical span, however MDIR may, due to its dynamic nature (monthly) express climate change conditions, whereas PMDFCI is static.

Figure 7b compares MDIR results between the 24th of July and the 23rd of August 2019, where a slight risk increase (0,1%), except for the minor risk class that decreased 0,5%, values may seem residual, however chlorophyll loss in some well adapted plants is not a rapid process.



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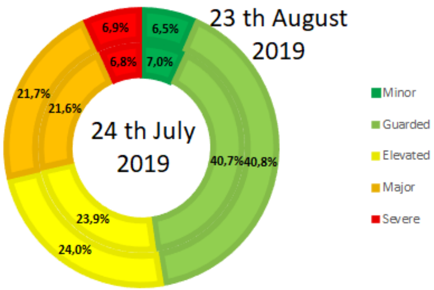

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Figure 7. a) Comparison bar chart between the two variations of the modernised model and PMDFCI, b) Comparison pie chart between the MDIR of 24th of July and 23rd of August 2019.

Model functional practicability is probably the most important characteristic of predicted results, hence the need to further exploit stressors and mitigation variables to optimise MDIR.

4. Conclusions

The integrated analysis of spatial slow and dynamic variables enabled by the InVest HRA model are valuable resources for forest fire research, and when fused with remote sensing satellite imagery combined with GIS processing, made possible the creation of fire ignition models MIR & MDIR. The produced models used literature proven valid variables and performed properly in identifying areas of high ignition risk.

The MIR model offers a generic well-defined severe risk area and may be useful as a general-purpose ignition risk map, whereas the MDIR offers a possible solution for monitoring and surveillance, despite the needed research and validation. MDIR model offers a solution that using NDVI indirectly includes the climate change, though being the only dynamic variable would benefit from short wave infrared, Normalized Distance Water Index (NDWI).

Tough much research is needed, the proposed models are fully updatable and built entirely with open source software, hence accessible to anyone.

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