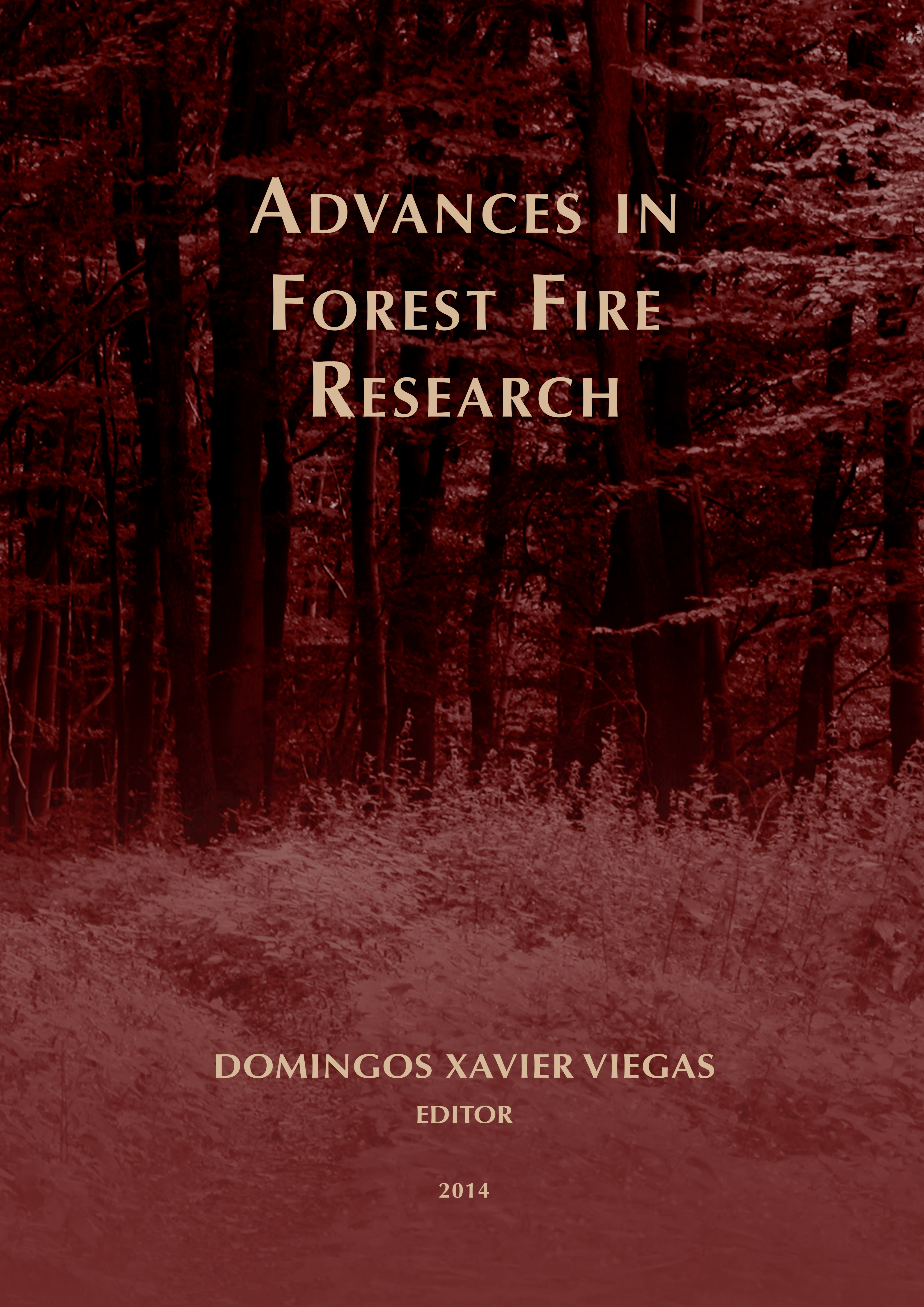

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Impacts of climate change on forest fire risk in Paraná State-Brazil

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Abstract
Forest fires are a global phenomenon due to the interaction between climate, fuels and human activities. Fires are also a critical component in the dynamics of planet earth and atmosphere. Recent advances in remote sensing products gathered via sensors on board satellites, have demonstrated the possibility of fire identification and monitoring on a global scale. The weather and climate are the major factors directly affecting fire and are being modified due to climate change caused mainly by man. There is an expectation of most researchers that changes in climate over the next 100 years will cause a major impact on forest ecosystems. The aim of this study was to determine, by decade, forest fire risk zoning for the State of Paraná, Brazil, based upon the scenarios predicted by the Intergovernmental Panel on Climate Change (IPCC) in 2007. Vegetation maps, fuel moisture, Monte Alegre Formula (FMA) for forest fire risk, slope, population density and road network, were used. These information, after being classified according to the risk of fire hazard, were weighted in a mathematical model. The determined values were then used to compose the Forest Fires Zoning Risk (ZRIF) per decade for the State of Paraná. Results showed that for the best scenario, which considers an increase of 1.8 ºC in the average temperature of the Earth by year 2100, there will be an increase in class extreme risk of forest fires, rising from 1.80% of the area of the State in 2020 to 8.49% in 2100. The same applies to the class of very high risk, which rises from 10.43% (2020) to 32.38% (2100). For the worst scenario, which considers an increase of 4.0 ºC in the average temperature of the Earth by 2100, the class of extreme risk rises from 2.18% (2020) to 22.72% (2100). The higher risk class rises from 13.93% (2020) to 55.95% (2100). It was concluded that, if the IPCC predictions were confirmed, there will be an increase in the number of occurrences and area affected by forest fires in the State of Paraná, which will require integrated actions to prevent and suppress forest fires to minimize environmental, social and economic damages.

Keywords*: forest fire risk, climate change, forest fire zoning risk, FMA fire risk*

1. Introduction

The effects of fire on the forests affect not only vegetation but also soil, fauna and atmosphere characteristics, and can be highly destructive when it is a forest fire. A fire occurs in the simultaneous presence of oxygen, fuel and heat source (Marques *et al.*, 2011). According to the terminology of wildfires proposed by the Food and Agriculture Organization (FAO), "fire hazard" is defined as the probability of starting a fire due to the presence and activity of active causal agents. Also, "fire hazard" is used to express the degree of involvement of fixed and variables factors that determine the ease of ignition, rate of spread, difficulty of control and impact of fires, usually expressed as an index (FAO, 2007).

The assessment of the risk of forest fires is a critical part in fire prevention, since for pre-suppression planning and fire-fighting tools are needed to monitor when and where a fire can occur or when its effects will be more negative (Chuvieco *et al.*, 2010).

Several factors may explain the ignition and spread of forest fires, such as: the characteristics of fuels, weather conditions, sources of ignition and topography. Fuel characteristics depend on the structure

and composition of vegetation, allied to anthropogenic factors (Marques *et al*., 2011). Another important ignition factor is the influence of human activities, which increase the risk of fire in the vicinity of road networks and urban areas (Cardille *et al*., 2001).
The risk of fires has been assessed by means of fixed and variable environment factors (e.g. fuels, weather and topography), that determine the ease of ignition, rate of spread, the difficulty of control, and the impact of forest fires (Vadrevu *et al*., 2010).
The importance of drawing up forest fire risk maps is evident for a long time (Show; Clarke, 1953). A very simple way to achieve a forest fire risk map is through the use of fire reports of previous years and plotting on a map the areas affected by fires. When there are multiple-year records, one can define a pattern for the areas of greatest occurrence and draw boundaries that define areas of risk (Brown; Davis, 1973; Chandler *et al*., 1983).
Several researchers have developed forest fires risk zones, using methods that allow to associate environmental factors with forest fires, allowing in this way to map the potential risk of fires according to the sensitivity of the factors related to fire. The main factors used in these studies, in order to establish different levels of forest fires risk, were: type of vegetation, characteristics of forest fuels, weather variables (temperature, air humidity, speed and direction of winds and precipitation), topography and ignition human activities (roads, demographics and usage type and occupation of land) (Salas; Chuvieco, 1994; Ferraz; Vettorazzi, 1998; Verde, 2008; Chuvieco *et al*., 2010; Marques *et al*., 2011; Oliveira *et al*., 2012).
Climate change can affect the number of fires that occur annually, the duration of the fire season and the area burned by fires. It also can increase the intensity of fire. Changes in these properties result in a direct influence of fire, increasing their frequency and intensity, and therefore, greater potential of fire (IPCC, 2007).
Several studies have demonstrated the impact of climate change on the behaviour of forest fires in various parts of the world, such as the research of Liu *et al*. (2012), on spatial patterns of fire occurrence and its future trend in Northeast China; Liu *et al*. (2010), on global trends of forest fire potential in the light of climate change, and the research conducted by Westerling and Bryant (2008), about climate change and California wildfires.
Flannigan *et al*. (2009a) reviewed the current understanding of what the future can bring with respect to forest fires. Research conducted in China by Tian *et al*. (2011), indicated a general increase in burned areas and in cases of fires, but with a considerable spatial variation, with some areas without alteration or even decrease in burned areas and the number of occurrences of fires.
Recent studies conducted by Flannigan *et al*. (2009b), suggest a doubling of burned areas, and an increase of 50% of the occurrences in several parts of the boreal forests by the end of this century. Fire seasons are expanding in the temperate and boreal regions and this trend should continue in the hottest regions of the world.
The Paraná is a State with a long tradition in the use and management of forest resources, mainly due to the exploration of extensive areas of forest with Araucaria covering almost the entire territory of Paraná in 20 mid-century (Maack, 2012). It is also the State in which occurred one of the biggest forest fires in the world, which in 1963 burned an area of 2 million hectares (20,000 hectares of plantations, 500,000 hectares of primary forests and 1,480,000 hectares of fields, secondary forests and brushlands) (Soares; Batista, 2007). And since that time the State of Parana has been a pioneer in research on control of forest fires in Brazil (Soares *et al*., 2009).
In view of the importance of forest fire risk zones and considering the hypothesis that the frequency and intensity of forest fires will increase in the light of global warming, the objective of this work was to evaluate the risk of forest fires for the State of Paraná, considering the scenarios predicted by the Intergovernmental Panel on climate change (IPCC) in 2007.

2. Methods

2.1. Study Area

The study area comprises the whole territory of the State of Paraná, located between the Parallels 22º 58' 30'' and 26º 43' 00'' South latitude and the Meridians 48º 05' 37''and 54º 37' 08'' West longitude. The territory comprises an area of 199,281 km^2, which corresponds to 2.34% of the total area of Brazil and 34.61% of the area of the southern region. In 2010, the State had 399 municipalities, 10,444,526 inhabitants and a population density of average 52.40 inhab/km^2, and much of this population live in urban area (85.30%). In the State of Paraná the altitudes range from sea level to 1,922 m at Peak of Paraná, located at Serra do Mar, highest elevation in the State and also in the southern region (IBGE, 2000, 2010).

Due to geographical location and topography, Paraná State has two dominant types of climate, having a third covering small land area between the coastline and the Valley of Ribeira (IAPAR, 1994). According to the Köppen classification (Trewartha; Horn, 1980), based on temperature and rainfall, Paraná State has the following climatic types: Cfa, Cfb and Af.

The less rainy months of June, July and August, shows that South and Southeast regions have rainfall between 350 and 450 mm, followed by Central and West regions, between 250 to 350 mm. The North region near the edge of the Paranapanema River, bordered by the State of São Paulo, rainfall is between 150 and 250 mm). The combination of low temperatures with occurrence of frosts and the decrease of precipitation make this quarter (June, July and August), most favourable to dry, making it susceptible to forest fires (Grodzki *et al*., 1996).

2.2. Collection and analysis of data

To obtain the necessary information to carry out the research, the following data set was used: historical series of temperature, relative humidity and precipitation of 28 weather stations operated by IAPAR from a period of 40 years (1970 to 2010); slope, aspect and elevation (INPE, 2008); demographic density (IBGE, 2010); map of State of Paraná with states and county boundary in 1:250,000 scale (IBGE, 2007); vegetation types map (Probio, 2005); road network map (DER, 2010).

The method consisted in the elaboration of preliminary risk maps for each variable under study: vegetation type, moisture of forest fuel, fire danger index (FMA), slope, elevation, aspect, population density and road network. These maps were integrated by means of a weighted sum of the characteristics of fuels, weather and ignition sources, according to the equation:

$$RIF=0.33*((MC+UMC)/2)+0.33*((FMA+DE-Hipso+Orient)/4)+0.33*((DD+SV)/2)$$

Where:
RIF = risk of wildfire computed in each unit of analysis;
MC = forest fuel;
UMC = forest fuel moisture;
FMA = fire danger index;
DE = slope;
Hipso = elevation;
Orient = aspect;
DD = population density;
SV = road network.

The risk map depending upon vegetation type (forest fuel), was prepared based on a map of vegetation type of PROBIO (2005). This variable was considered static for the period under examination. The 55 vegetation types found in this survey were grouped into the following classes: agriculture, pasture/fields, forest cover, forest cultivation and no information.

The forest fuel moisture was estimated by the equation proposed by Simard (1968):

$$E = 21.06 - 0.4944*H + 0.005565*H^2 - 0.000638*H*T \quad (H > 50)$$

Where:
E = forest fuel moisture, in percentage;
H = relative humidity, in percentage;
T = air temperature in °C.

Two scenarios were generated according to the IPCC report of 2007: (i) The best scenario, considering 1.8 °C increase in the average temperature of the Earth by 2100, (ii) The worst scenario, considering 4.0 °C increase in the average temperature of the Earth until 2100.
For the estimation of the necessary weather variables, stochastic simulations were carried out with the program PGECLIMA_R (Das Virgens Filho *et al*., 2011), for the period of 2010 to 2100.
The cumulative index of fire danger was calculated for the period of 2010 to 2100 and for both scenarios, using the fire risk index called Monte Alegre Formula (FMA). After generating the indexes, the values were classified into 5 classes through the method of Quantile and interpolated using Kriging method.
The variables slope, aspect and elevation were considered static variables for the analysis, and were generated using TOPODATA data set (INPE, 2008). Ratings were established on the basis of Soares and Batista (2007), Salas and Chuvieco (1994) and Fernandez and Vettorazzi (1998), respectively.
To generate the variable population density (dynamic variable), data were used from Brazilian Institute of Geography and Statistics (IBGE) related to 1991, 2000 and 2010 census for each municipality in the State of Paraná, as well as population estimates from 2000 to 2009. Initially it was necessary to estimate the population every decade for further calculation of the density. For this the method of Von Sperling (2005) was used. Population projections were generated using descending rate of growth. The observed values for the population density by municipality were distributed into five classes adapted from Guillhermo Julio (1992).
Considering that distance from the road system is inversely proportional to the risk of forest fire, buffers were established from the roads and railway network (DER, 2010). This was adapted from Salas and Chuvieco (1994) method. This variable was considered static for the analyzed period.
The final risk map was obtained applying GIS algebra operations between the preliminary risk maps (Salas; Chuvieco, 1994, Souza *et al*., 1996, Ferraz; Vettorazzi, 1998). After that, the risk map was classified into five classes of risk (low, moderate, high, very high, extreme), using the Quantile method. Finally, maps were generated for both, best and worst scenarios.

3. **Results and discussion**

The forest fire risk map depending on the vegetation cover featured a 4,263,177 ha (21.53% of the area of the State) in the extreme risk class, while the area for the very high class indicated 6,187,629 ha (31.25%). These areas where concentrated in the East and Northwest of the State.
In the eastern region are the most extensive forest fragments in the State, while the Northwest region is dominated by extensive grazing areas. These higher-risk areas reflect the largest vegetation flammability when compared with other types of vegetation found in the State of Paraná.
Considering the fuel moisture variable, in the best case scenario simulation, classes were not observed with very high and extreme risk in 2020. While in 2100 these classes have covered more than half of the State area (56.08%). The extreme class concentrated in the northern region with 11.97% of the State area. The worst case scenario simulation also failed to provide the most extreme classes (very high and extreme) in 2020, when compared to the best case scenario. However, in 2100 much of the State was ranked in the extreme risk of forest fire, reaching 91.33%. The moisture content is the most

important property that controls the flammability of living and dead fuels (Soares; Batista, 2007). Therefore, it has great influence on the risk of fire (ADAB *et al*., 2013). The moisture of forest fuels is the result of climate and atmospheric conditions. The results showed that as climate becomes drier over the years, according to the IPCC scenarios, there were more extensive areas with drier forest fuels and therefore, more dangerous and more flammable.

Regarding the simulation to the best case scenario of the FMA, it was observed a discrete spatial variation in the behaviour of the index, with little variation in terms of area in the State. In 2020 the high, very high and extreme classes resulted in 62.58% of the State area, keeping this extension in 2100. For the worst case scenario, it was noticed a significant spatial variation in the analysis period, with very high and extreme classes with more than half of the State at the end of the period. In this scenario the high and very high classes resulted in 56.82% in 2020, reaching 96.89% of the area in 2100.

For the slope variable, the State presented largely in low and moderate risk classes. The low risk class totalled 12,802,087 ha (64.41% of the area of the State) and the moderate class 3,845,465 ha (19.35%). The extreme risk concentrated in the Serra do Mar and Ribeira Valley and corresponded to 3.00% of the total area. According to Adab *et al*. (2013), the slope is one of the parameters that influence the rate of spread of fire. The fire runs faster uphill than downhill. In addition, the rate of spread of fire can increase on the steepest slopes, because the flames are tilted closest to the surface of the soil, and the process of heat convection may be increased by the wind.

The risk of fire in terms of elevation showed that much of the State was ranked in high risk and very high, totalling 98.23% of area (altitude less than 1,200 m above sea level). As Hernandez-Leal *et al*. (2006), the altitude is a physiographic variable that is associated with the temperature, moisture and wind. Therefore, it plays an important role in fire propagation. The altitude influences the structure of the vegetation, air moisture and fuel. It was observed that the humidity and temperature have greater influence over fire in areas with higher altitude. It has also been reported that the fire behaviour trends are less severe on higher places due to higher rainfall (Chuvieco; Congalton .1989).

The classes of fire risk due to the aspect of the slopes were low, with 36.59% of the area, followed by a very low, with 25.20% and high, with 12.93 %. The aspect of the slopes is correlated with the amount of solar energy that an area receives (Soares; Batista, 2007). The north-facing slopes receive more sunlight and high temperatures, high winds, low humidity and low fuel moisture in the southern hemisphere. Therefore, the vegetation is typically drier and less dense in the northern slopes (Vadrevu *et al*., 2010; Soares; Batista, 2007). Because of this, the driest fuels are more exposed to ignition (Adab *et al*., 2013).

The simulation of population density and its classification in terms of risk of forest fire showed a continuation of higher risk in the North, East and West of the State. The State had, in 2010, 76.41% of its area in the low risk class, which fell in the period under examination, passing to 69.70% of the area. The extreme risk class increased from 7.83 % to 12.72%, which represented an increase of 62.4%. Humans are the cause of the vast majority of fires and therefore, the population density is a factor which expresses the omnipresent effect of population on the ignition and spread of fire. In this sense, Marques *et al*., 2011, claim that the population density has been singled out as the main source of ignitions of fires in Portugal.

The road network has an area of influence of 831,534 ha (4.38% of the State area). This area is divided into 170,692 ha with low risk, 167,645 ha with moderate risk, 166,028 ha with high risk, 164,268 ha on the degree of risk too high and 162,900 ha in degree of extreme risk. The road network showed no influence on 95.62% of the area of the State. It is necessary to emphasize that human activities are one of the basic factors that affect fire occurrences (Xu Dong *et al*., 2005). Due to more intensive human activities, the fire risk is larger and offers plenty of opportunity for the unexpected fire ignition (Alencar *et al*., 2004). Proximity of roads and road density are potentially important parameters once the roads facilitate access of people in areas of forest and pasture and this can cause fires (Jaiswal *et al*., 2005).

In figures 1 and 2 are presented forest fires risk zones in the years 2020 and 2100, for the best scenario. In the first decade (2020) the risk was concentrated in the moderate and high classes, with 33.04% and 54.64%, respectively. Areas located in the North region of the State and in the surrounding areas of the metropolitan region of Curitiba, concentrated much of the extreme risk of forest fires, which totalled 1.80% of the total area. This value increased in the following decade, passing to 2.51%. The same behaviour is observed for the very high class, ranging from 10.43 % to 13.82 %.
This behaviour has remained throughout the period under examination. In 2100, the area corresponding to the low risk class was 0.01 %, while the moderate class corresponded to 7.66 %, the high class 51.47%, very high class to 32.38% and extreme class to 8.49%.

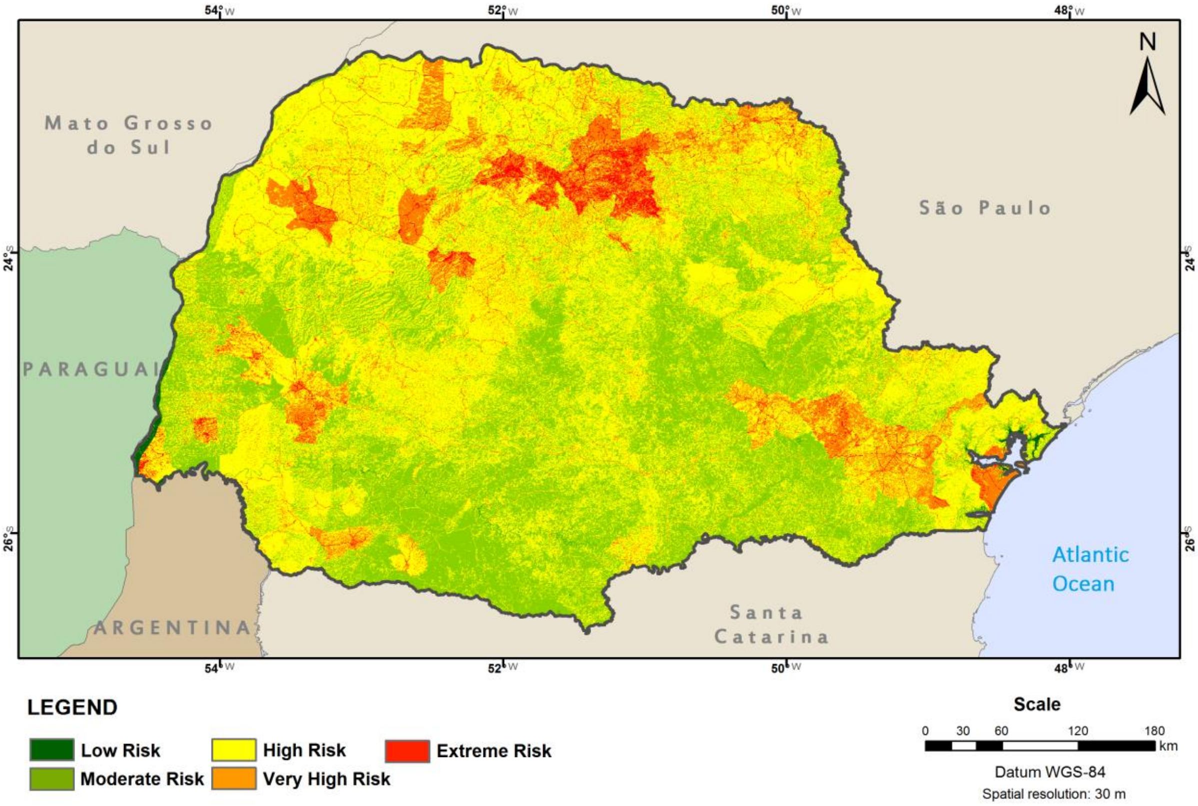

Figure 1. Risk of wildfire in 2020 (best case scenario).

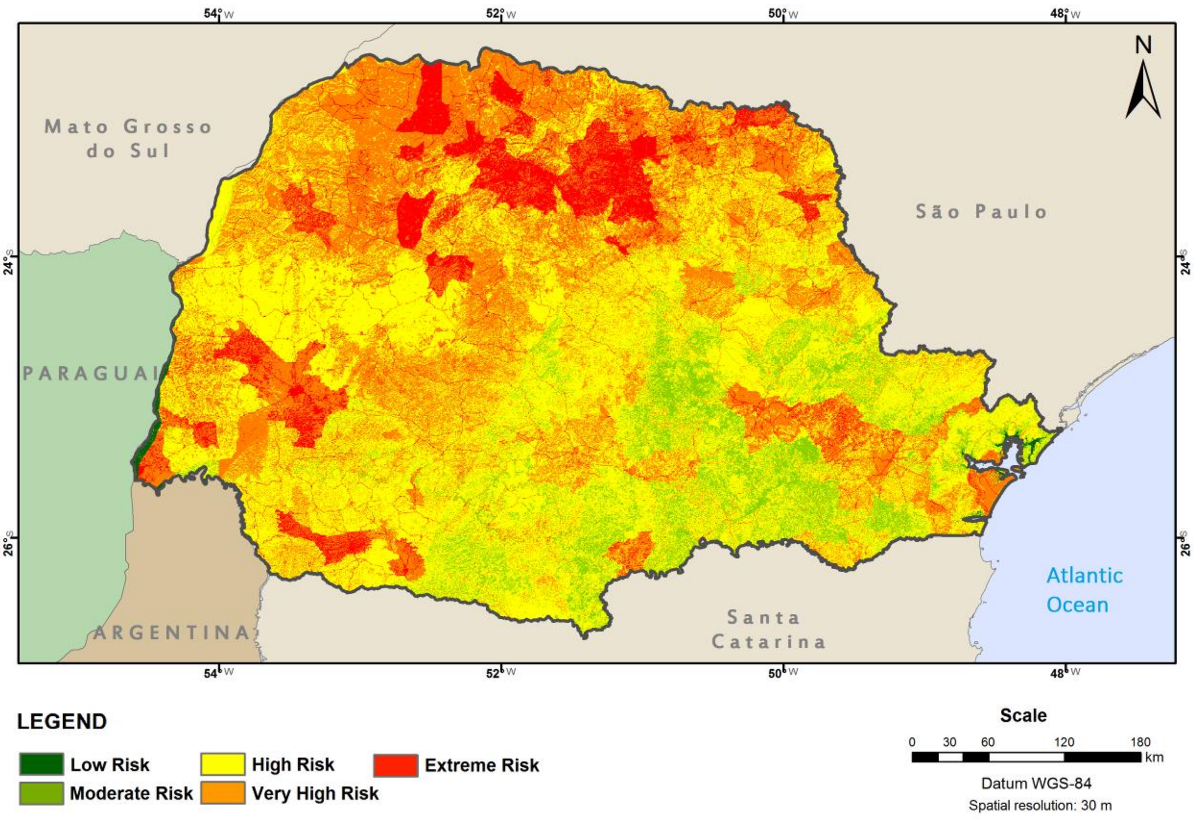

Figure 2. Risk of wildfire in 2100 (best case scenario)

In figures 3 and 4 are presented the forest fires risk zones, in the years 2020 and 2100, for the worst case scenario. In the 2020 decade, much of the State performed at high-hazard class (51.74% of the area), followed by the moderate (32.08%) and very high (13.93%). The class of extreme danger, with 2.18% of the area, passed the decades following the 3.54% and 5.98%, respectively.

At 2100 the State failed to provide more area in the low risk class and the moderate risk class corresponded to 0.07% of the State. The high class, that in 2020 was 51.74%, showed 21.27%. The classes very high and extreme, both with significant increment, represented 55.95% and 22.72% of the total area.

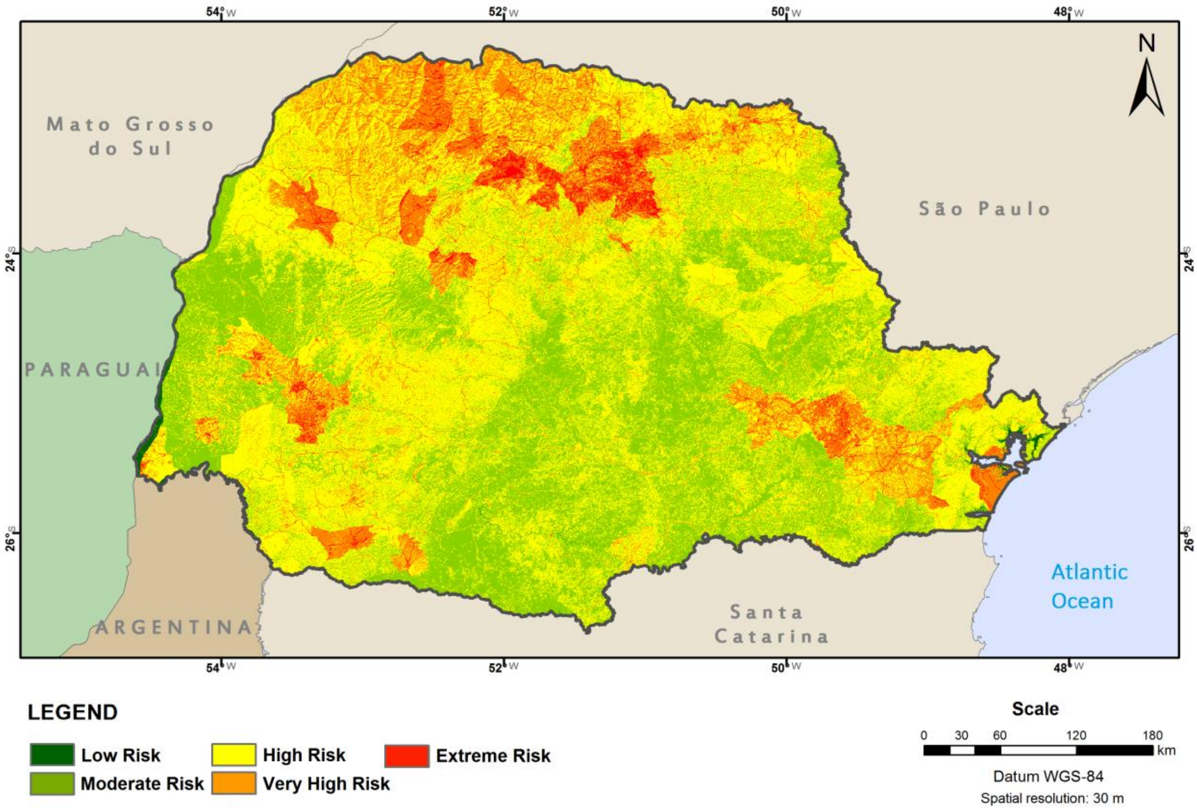

Figure 3. Risk of wildfire in 2020 (worst case scenario)

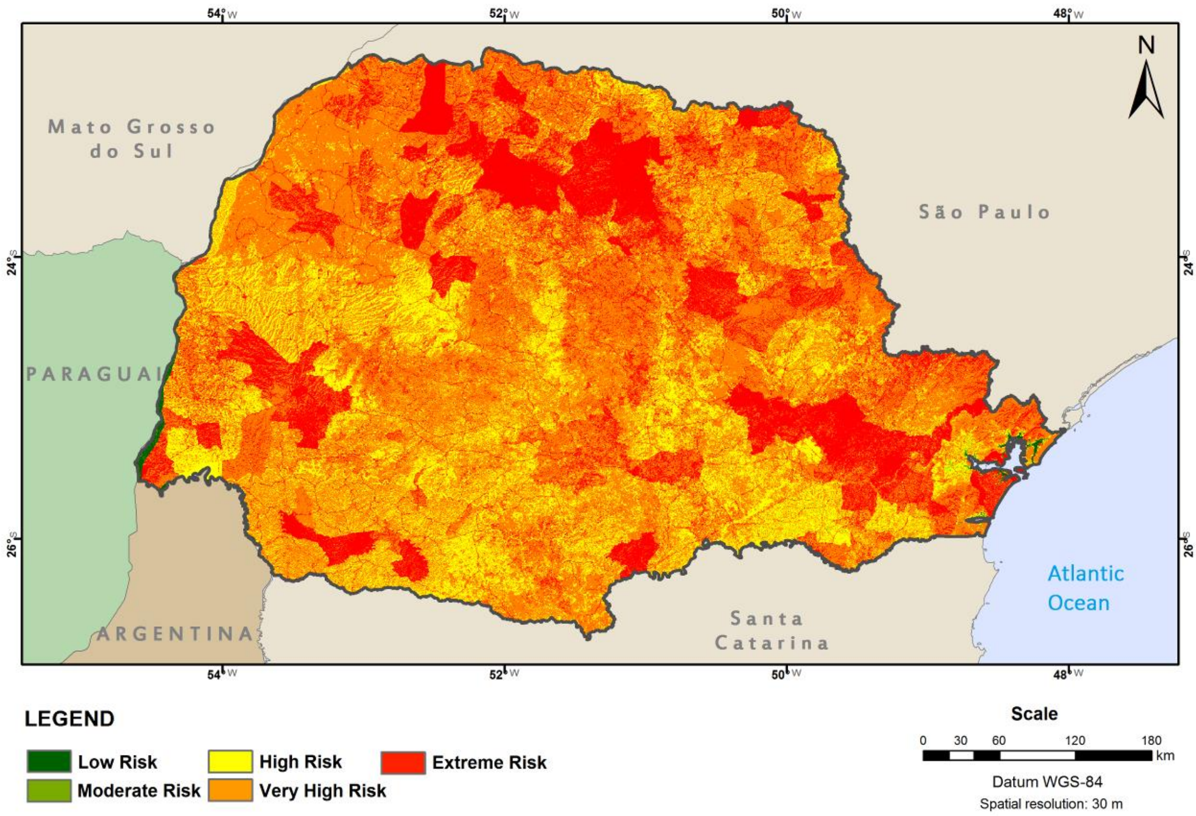

Figure 4. Risk of wildfire in 2100 (worst case scenario)

4. Conclusions

The dynamic variables (demographic density, fuel moisture, fire danger index (FMA) and forest fire risk zoning), showed an increase in higher classes of danger from fires over time. This behaviour was observed for both the best and the worst scenarios of temperature increase (in accordance with the IPCC).

The data integration model used showed generate consistent results, considering that the mapping of the exposure classes obeyed an evolution according to the decades.

The hypothesis that there will be an increase in the risk of forest fires in the event of an increase in the average temperature of the Earth, was accepted. It is concluded that, if the IPCC predictions are confirmed, there will be an increase in the number of fire events in the State of Paraná, which will require integrated actions for preventing and fighting forest fires to minimize possible environmental, social and economic damages.

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