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Forest fire risk zoning for the metropolitan region of Curitiba, Paraná, Brazil

Heitor Renan Ferreira, Antonio Carlos Batista, Alexandre França Tetto & Daniela Biondi

Federal University of Paraná, Forest Engineering Department, Curitiba-PR, Brasil. bmheitorf@gmail.com, batistaufpr@gmail.com, tetto@ufpr.br, dbiondi@ufpr.br

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Abstract
Forest fires are becoming increasingly frequent throughout the globe, influencing socioeconomic and environmental aspects and endangering ecosystems and life. The forest fire risk zoning is an auxiliary tool for elaborating and implementing preventive policies. The present study aims to execute the forest fire risk zoning for the metropolitan region of Curitiba, Paraná, Brazil, testing its efficiency through the relationship with geolocated fires that occurred from 2011 to 2016. Thematic maps were made through information related to demographic density, road system, land use and cover, slope, orientation and altimetry of the terrain. The efficiency of the proposed zoning, 45.8% and 44.0% of the geolocated fires that occurred in the study area in the period 2011 to 2016 were present in areas considered with "very high" and "high" risk, respectively, demonstrating that the proposed zoning can be used to develop prevention policies for the metropolitan region of Curitiba.

Keywords: wildfire; urban-rural interface; wildland-urban interface; fire hazard; fire prediction.

Zonificación del riesgo de incendios forestales para la región metropolitana de Curitiba, Paraná, Brasil

Resumen
Los incendios forestales son cada vez más frecuentes en todo el planeta, influyendo en aspectos socioeconómicos y ambientales, poniendo en peligro los ecosistemas y la vida. La zonificación de riesgo de incendios forestales es una herramienta auxiliar para la elaboración e implementación de políticas preventivas. El presente estudio tiene como objetivo ejecutar la zonificación de riesgo de incendios forestales para la región metropolitana de Curitiba, Paraná, Brasil, probando su eficiencia a través de la relación con incendios geolocalizados ocurridos en el período de 2011 a 2016. Se realizaron mapas temáticos a través de información relacionada con los factores demográficos. densidad, sistema vial, uso y cobertura del suelo, pendiente, orientación y altimetría del terreno. De la eficiencia de la zonificación propuesta, el 45,8% y el 44,0% de los incendios geolocalizados ocurridos en el área de estudio en el periodo 2011 al 2016 estuvieron presentes en áreas consideradas con riesgo "muy alto" y "alto", respectivamente, demostrando que la zonificación propuesta La zonificación se puede utilizar para desarrollar políticas de prevención para la región metropolitana de Curitiba.

Palabras clave: incendio forestal; interfaz urbano-rural; interfaz urbano-forestal; peligro de incendio; predicción de incendios.

1 Introduction

Increasingly, forest fires have impacted different regions of the Earth, directly and indirectly affecting socio-economic and environmental aspects, as well as flora, fauna, soil, and atmospheric air [5,16,24,25].

The latest report released by the Intergovernmental Panel on Climate Change (IPCC) points out that the forecast is for an increase in average land temperature, which may cause, among other adversities, water deficit in many regions, which in turn makes the environment prone to higher numbers of events related to forest fires.

Forest fire risk zoning is an auxiliary tool for the elaboration and execution of preventive policies. The

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government can use it to train its personnel and allocate resources, minimizing possible future losses.

The occurrence and propagation of forest fires are mainly influenced by the combustible material's quantity, type, arrangement, humidity, climatic conditions, topography, and vegetation type [24]. Fire risk maps integrate this information into their composition through a geographic information system [4].

In fire planning, the development of regional fire risk maps presents greater accuracy and efficiency than maps produced at larger scales [4].

With the advancement of geospatial programming techniques, several initiatives have been developed for automatic systems for calculating the risk of fires in vegetation. Despite considering variables with slight variation in a short time, such as topography and land use and cover, these systems can monitor daily changes in meteorological variables.

The Curitiba metropolitan region has extensive vegetation areas, including rural properties with agropastoral activities, remnants of native vegetation, and urban lots with vegetation. According to Ferreira [10], from 2011 to 2016, the metropolitan region of Curitiba presented 5,472 records of forest fires, with a burned area of approximately 2,271.45 ha, evidencing the problem caused by this event for the region.

With the increasing evolution of anthropic activities in the metropolitan region of Curitiba, involving the expansion of urban areas towards rural areas, there is a tendency to increase events related to fires in vegetation, directly and indirectly influencing society, leading it to the closest conviviality with fire.

The present study aims to execute the forest fire risk zoning for the metropolitan region of Curitiba, evaluating its efficiency when compared to the registered and geolocated fires from 2011 to 2016 in the study area.

2 Materials and methods

2.1 Study area

The study area comprises 29 municipalities in the Metropolitan Region of Curitiba (MRC). The MRC has a total area of 16,579.58 km² and is located in the eastern part of the state of Paraná, in Brazil's southern region. In 2017, the estimated population was 3,592,465 inhabitants. Its UTM center coordinates are 22S N 7,186,559 m and E 673,674 m [13].

Fig. 1 shows the list of municipalities presents in MRC and its location.

The metropolitan region of Curitiba is located in a region of the Cfb and Cfa climate. Cfb is a temperate climate, without dry season, with fresh versions and Cfa is a subtropical climate, without dry season, with fresh summers and frosts uncommon [3, 17].

Regarding the original vegetation, the study area is part of a phytogeographic region bordering natural fields and Araucaria Forest, including Dense Ombrophilous Forest areas to the north and east of the study area, integrating the Atlantic Forest biome [17].

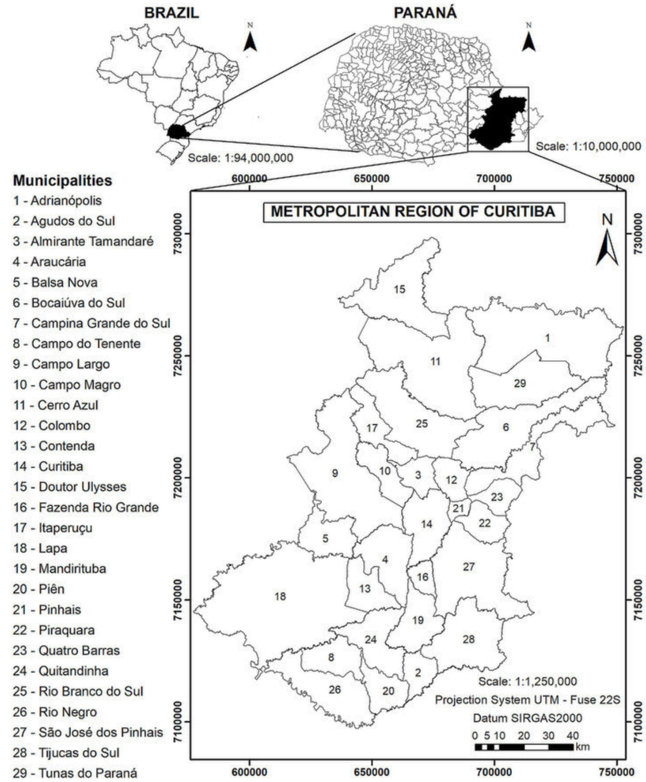

Figure 1. Location of the municipalities presents in the metropolitan region of Curitiba.
Source: The authors.

2.2 Fire risk zoning and research variables

For the preparation of the forest fire risk zoning in the metropolitan region of Curitiba, a superposition of thematic maps was performed according to a weighting model based on the adaptation of the methodologies used by Oliveira [19], Batista et al. [4] and Kovalsyki et al. [15]. These authors used coefficients ranging from 0 to 5 to classify the variables of interest, with subsequent insertion in the equation proposed in their research.

The thematic maps were divided into two groups: fire risk map according to human influence and fire risk map according to environmental factors.

The fire risk map, according to human influence, comprised the demographic density and the road system. There are indications that the anthropic presence is the primary causal agent in the metropolitan region of Curitiba [10,11], not differing from other urbanized regions and presenting areas of wildland-urban interface around the globe. Due to the human presence as a causal agent, different authors, such as Ho et al. [12] and Batista et al. [4] proposed to act with demographic density in risk analysis.

Also, Batista et al. [4], Ferraz and Vettorazzi [9], Kovalsyki et al. [15], Salas and Chuvieco [22], Ribeiro et al. [20], Ho et al. [12], Koproski et al. [14], Mota et al. [18] and Yathish et al. [26] worked with the influence of roads as a risk agent for fires, since highways are related to the anthropogenic presence in the environment.

The fire risk map, according to environmental factors, was based on land cover and use, slope, altimetry, and terrain orientation.

The cover and use of the soil demonstrate the importance of risk zoning because it presents the presence or absence of vegetation, as well as the different types of this, and may present greater or lesser danger of ignition and propagation, such as more excellent flammability of conifers when compared to various hardwoods [4,24].

Regarding topography, uphill areas tend to have a faster spread of fire than sloping areas, a factor related to convective phenomena, radiation, and conduction [24].

Regarding the orientation of the slopes, in the Southern Hemisphere, there is a higher incidence of the sun's rays on the faces facing north, followed by the west face, demonstrating that both faces receive a more significant amount of energy than the other ones [4,20,24].

Finally, altimetry demonstrates that low elevations present more extended fire risk stations than high elevations. Also, the mountain tops and valley bottoms present different burning conditions during the day because there is a difference in wind currents and temperature and humidity in both locations. Valley funds have higher fire propagation potential during the day, and mountain tops have the most significant potential at night [4].

2.3 Fire risk zoning and research variables

The demographic density map was elaborate with Brazilian Institute of Geography and Statistics (IBGE) information in the 2010 demographic census [6], using the census sector delimited by this organization. Each census sector presents the number of inhabitants in a variable area, thus obtaining the demographic density by sector.

The road system influence map was realized using the information from the Department of Highways of Paraná [7]. A buffer of 1,000 m radius of the center of the road was carried out, thus characterizing the area under the influence.

Table 1 presents the classification of demographic density and distribution of the road system according to Batista et al. [4].

2.4 Fire risk map according to environmental factors

The risk map according to land cover and use was realized using the information contained in collection 5.0 of the year 2016 of the Annual Mapping Project of Land Cover and Use in Brazil [2], which uses satellite images and a data structure linking different variables for mapping the country's land cover and use. Subsequently, a risk classification was performed based on the variables described in the mapping obtained based on the studies of Batista et al. [4] and Kovalsyki et al. [15] (Table 2).

Table 1.
Classification of the variables that compose the risk map according to human influence.

Demographic density		
Inhabitants per km²	**Risk**	**Coefficient**
Up to 40.00	low	1
40.01 - 60.00	moderate	2
60.01 - 80.00	high	3
80.01 - 100.00	very high	4
Above 100.00	extreme	5
Distribution of the road system		
Class	**Risk**	**Coefficient**
With influence	yes	1
Without influence	no	0

Source: The authors.

Table 2.
Land cover and use classification for fire risk map according to environmental factors.

Classification	Risk	Coefficient
Water	null	0
Urban infrastructure Other non vegetated areas Mining	low	1
Natural forest	high	3
Mosaic agricultura and pasture Agriculture Pasture	very high	4
Grassland	extreme	5

Source: The authors.

Table 3.
Topography classification for fire risk map according to environmental factors.

Variable	Classification	Risk	Coefficient
Slope	Up to 15%	low	1
	16% - 25%	moderate	2
	26% - 35%	high	3
	36% - 45%	very high	4
	≥ 46%	extreme	5
Altimetry	Até 600.00 m	extreme	5
	600.01 m – 900.00 m	very high	4
	900.01 m – 1,200.00 m	high	3
	1,200.01 m – 1,500.00 m	moderate	2
	Above 1,500.00 m	low	1
Orientation	112,51° - 247,50°/(SE/S/SW)	low	1
	67,51° - 112,50°/(E)	moderate	2
	22,51° - 67,50°/(NE)	high	3
	247,51° - 337,50°/(NW/W)	very high	4
	337,51° - 22,50°/(N)	extreme	5

Source: The authors.

Urban infrastructure, other non-vegetated areas, and mining were considered as having a "low" danger because of the existence of vacant lots in these areas that may have vegetation fire, making the classification "null" unfeasible since some areas with vegetation were not covered by the spatial resolution used by MAPBIOMAS (30 m).

To obtain the thematic maps of fire risk according to altimetry, slope, and terrain orientation, images of the Satellite Alos Palsar, with a spatial ratio of 12.5 meters, using the digital elevation model. The slope of the terrain was obtained through the tool "slope" and the orientation of the terrain by the tool "aspect", both present in version 10.5 of the ArcGIS software. The recommendations of Batista et al. [4] were followed for the classification (table 3).

After making the thematic maps by counting pixels of the raster-type files in each class, the area occupied in each risk classification was calculated.

2.5 Integration of thematic maps

To complete the thematic maps, the "raster calculator" tool of Arcgis software version 10.5 was used, thus relating the coefficients found in the pixels of each thematic map.

The weighting model used was adapted from Oliveira [14] and Kovalsyki et al. [15]:

$$FFRZ = (0,655 \times DD + 0,655 \times RS) + [(0,29 \times S\% + 0,11 \times OE + 0,1 \times AL) + (0,8 \times LCU)] \quad (1)$$

Where:
DD = Demographic density.
RS = Road system.
S% = Slope.
OE = Orientation.
AL = Altimetry.
LCU = Land cover and use.

The weighting model used is indicated for the elaboration of forest fire risk zoning in the state of Paraná. It presents similarities in the variables used, as well as presents climatic conditions similar to the study area.

Six classification classes were obtained for forest fire risk zoning, distributed according to the classification method "natural break" of the software ArcGis.

Table 4 presents the classification of the fire risk zoning and the values of each class.

To evaluate the effectiveness of the proposed risk zoning, the forest fires geolocalized in the study area from 2011 to 2016 were used using the Ferreira [10] database.

By relating the geolocation points of the forest fires with the proposed zoning classification, we can verify the number of points per class and, consequently, the percentage of concentration of fires in relation to risk zoning.

3 Results

Fig. 2A and 2B present the fire risk maps according to demographic density and road system, respectively.

The risk map, according to demographic density, showed that 14,284.47 km² (86.1%) of the study area has a "low" risk. The "moderate" risk occupied the area of 606.42 km² (3.7%), the "high" area of 232.3 km² (1.4%), the "very high" area of 194.92 km² (1.2%), and the "extreme" risk the area of 1,261.33 km² (7.6%).

It was observed that the regions with the highest risk comprise the urbanized municipal areas, especially Curitiba. As you move away from the urban area towards peripheral areas, there is a decrease in risk, as the demographic density is lower in rural areas.

The risk map, according to the road system, showed that 2,396.43 km² (14.5%) of the study area is under the influence of highways, while the area without influence was 14,183.22 km² (85.5%). The municipalities with a more significant extension of highways will, therefore, have a larger area under the influence, providing greater circulation of vehicles and anthropic presence.

Table 4.
Risk classes for the proposed zoning.

Class	Risk
0.0	null
1.35 - 3.15	low
3.16 - 4.52	moderate
4.53 - 5.36	high
5.37 - 6.49	very high
> 6.5	extreme

Source: The authors.

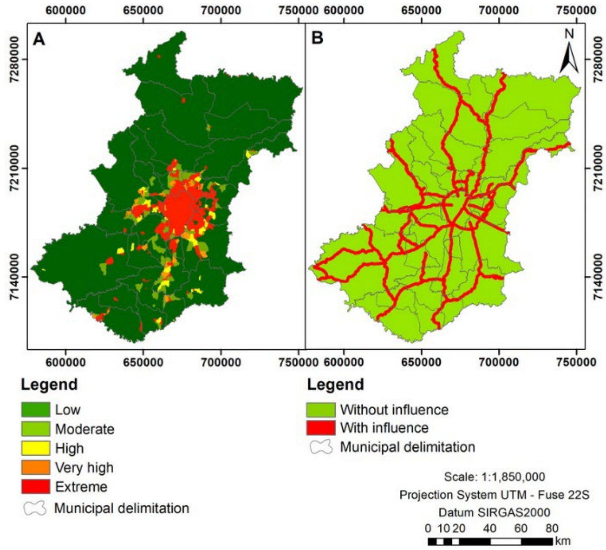

Figure 2. Fire risk map for metropolitan region of Curitiba according to: A) Demographic density; B) Road system.
Source: The authors.

Figs. 3A, 3B, 3C, and 3D presented the fire risk maps according to the land cover and use, slope, orientation, and altimetry.

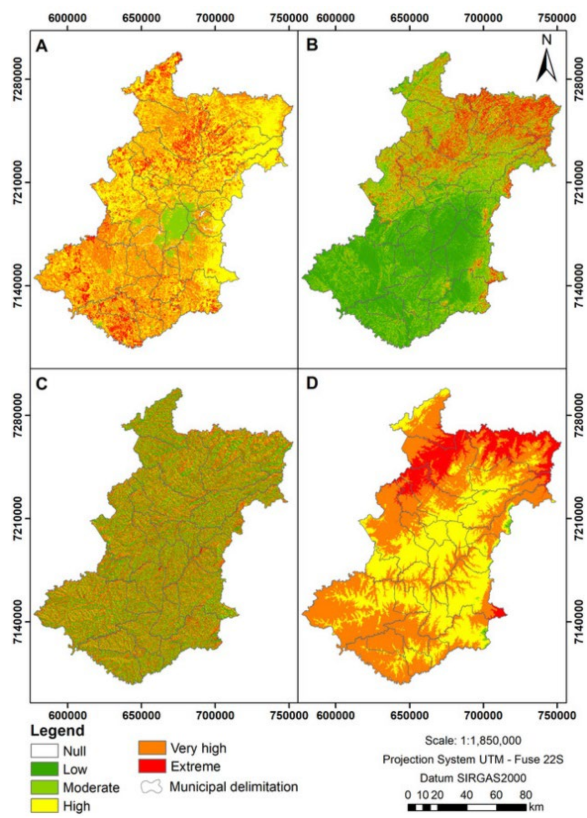

Figure 3. Fire risk map for metropolitan region of Curitiba according to: A) Land cover and use; B) Slope; C) Orientation; and D) Altimetry.
Source: The authors.

Table 5.
Area that the fire risk classification occupied in fire risk map according to land cover and use.

Risk	Land cover and use	
	Area (km²)	%
Null	80.67	0.5
Low	704.82	4.3
Moderate	-	-
High	8,654.96	52.2
Very high	5,181.45	31.2
Extreme	1,957.68	11.8
Total	**16,579.58**	**100**

Source: The authors.

Table 6.
Area that the fire risk classification occupied in fire risk map according to slope and orientation.

Risk	Slope		Orientation	
	Area (km²)	%	Area (km²)	%
Null	-	-	-	-
Low	7,823.94	47.2	6,058.02	36.5
Moderate	3,552.72	21.4	1,966.91	11.9
High	2,231.20	13.5	2,061.39	12.4
Very high	1,516.11	9.1	4,182.62	25.2
Extreme	1,455.62	8.8	2,310.64	13.9
Total	**16,579.58**	**100**	**16,579.58**	**100**

Source: The authors.

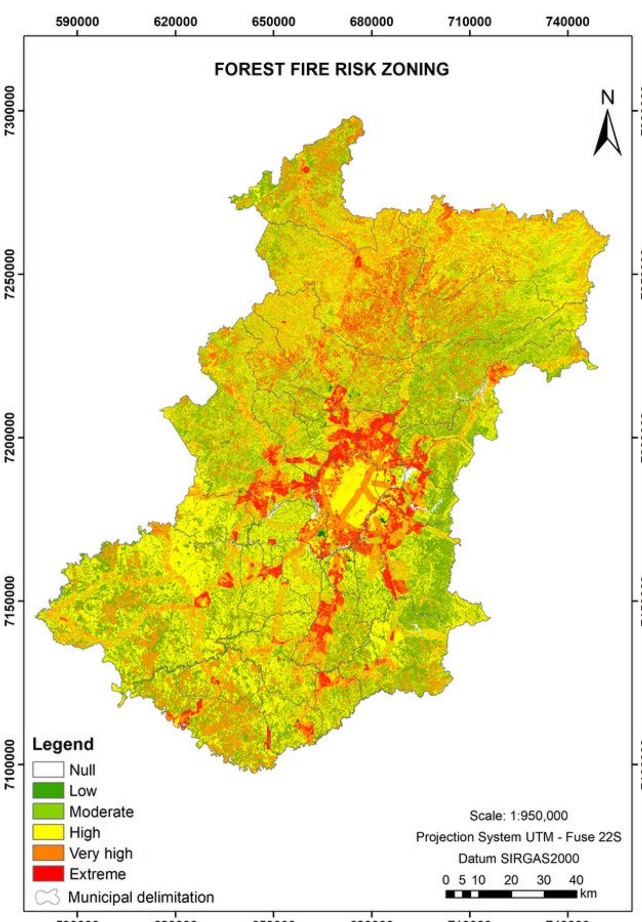

Figure 4. Forest fire risk zoning for metropolitan region of Curitiba.
Source: The authors.

Table 7.
Relationship of forest fire geolocation from 2011 to 2016 with the proposed risk zoning.

Classification FFRZ	Forest fire geolocalization (2011-2016)	
	n°	%
Low	36	0.8
Moderate	28	0.6
High	1,915	44.0
Very high	1,994	45.8
Extreme	381	8.8
Total	**4,354**	**100**

Source: Ferreira [10] and the authors.

There were small divergences between the values available with the MAPBIOMAS files (table in .xls format and raster file), so we chose to use the calculated values of the pixels of the raster file using the ArcGis software.

Table 5 and 6 shows the area that the fire risk classification occupied in each variable.

For the risk map according to land cover and use, the "high" class presented the largest dimensions in the study area (8,654.96 km² - 52.2%). It was found that urbanized regions present mostly areas with "low" risk, as they refer to urban structures. The other regions showed variations according to land cover and use.

Regarding slope, it is observed that most of the study area (7,823.94 km² - 47.2%) is present in the classification of "low" risk. The same occurred for the orientation variable, which presented in the same classification an area of 6,058.02 km² (36.5%). The variable altimetry presented the class "very high" (8,521.31 km² - 51.4%) in most of the study area.

Fig. 4 presents the forest fire risk zoning for the study area.

The result of the thematic maps integralization indicated that 6,946.39 km² (41.9%) of the study area presented the "high" risk classification, followed by 4,575.5 km² (27.6%) of "moderate" risk and 3,744.29 km² (22.6%) of "very high" risk. Furthermore, the "extreme" risk occupied the area of 1,192.74 km² (7.2%), the "null" risk the area of 80.67 km² (0.5%) and the "low" risk the area of 39.99 km² (0.2%).

Table 7 demonstrates the relationship with the risk classes found in the present study.

Regarding the efficiency of the proposed zoning, 45.8% and 44.0% of the geolocated fires that occurred in the study area in the period 2011 to 2016 were present in areas considered with "very high" and "high" risk, respectively.

4 Discussion

Regarding the risk classification according to demographic density, Batista et al. [4] find that 77.14% of the area of the state of Paraná is present in the "low" risk classification. In the state of Santa Catarina, contiguous to Paraná, Ho et al. [12] observe that population density is classified as "low" risk in 65.9% of the analyzed area for the scenario from 2010 to 2020. Both studies corroborate the present research since rural areas have a more significant extension in the national territory.

To Kudremukh National Park, Yathish et al. [26] verify a high relationship between occurrences of forest fires and human activities, including highways. Ajin et al. [1] observe that anthropogenic factors are the most relevant for forest fires in their study area (Idukki Wildlife Sanctuary). Tetto et al. [25] recommend in their study in the Irati National Forest that the areas with the highest flow of people should have a greater intensity of preventive activities.

Batista et al. [4] observed that for the state of Paraná, the value of 15.18% of areas with an influence of the road system is similar to that found in the present study since it is the same state. In Santa Catarina, Ho et al. [12] verified that 2.39% of the state was under the influence of the road system, a value lower than the present study.

In the fire risk map according to land cover and use, it is verified that for the state of Paraná, Batista et al. [4] identify that 34.03% of the study area has an "extreme" risk classification, with values decreasing to the "low" risk. Possibly, the difference in the scale of analysis of the metropolitan region of Curitiba, compared to the state of Paraná, shows that because there is more urbanization in the MRC, there will consequently be a more evident "low" risk classification. Furthermore, the MRC predominates natural forest and agricultural activities compared to rural formations and forest plantations, reducing the presence of the "extreme" risk classification.

Mota et al. [18] verify that for the state of Mato Grosso, Brazil, the existing particularities of the Cerrado biome increase the ignition potential. Kovalsyki et al. [15] verify that land cover and use present 94.5% of the area of Vila Velha State Park in risk classes equal to or above "high," a value similar to that found in the present study despite the specificities and phytophysiognomy of their study area. For the state of Santa Catarina, Ho et al. [12] observe that the most frequent risk class is "high", occupying 41.33% of the state area, followed by the "extreme" risk class with 38.34%, differing from the present study.

Regarding slope, different studies located in the state of Paraná present high percentages of "low" risk, as verified by Ribeiro et al. [20], Koproski et al. [14], and Kovalsyki et al. [15] (99.3%, 83.76% and 72.1% respectively). In Santa Catarina, Ho et al. [12] found a value of 49.3% for the "low" risk classification, lower than the other studies, demonstrating a greater slope and, consequently greater possibility for the propagation of fire in this state.

The orientation with the "low" risk classification is also predominant in the studies: Kovalsyki [15], which has a value of 44.4% coverage; Batista et al. [4], which also has the "low" hazard class as the most prevalent for the state of Paraná, with a value of 32.80%; and Ho et al. [12], which has 39.14% in the same class. Koproski et al. [14] found that 43.23% of their study area was classified as "very high", demonstrating a higher rate of incident radiation than the other studies.

Regarding altimetry, the different studies were analyzed to corroborate the present study regarding the predominance of a higher-risk class. Kovalsyki et al. [15] show that 74.7% of their study area has a "very high" class, followed also by Koproski et al. [14] with 95.29% coverage of their area and Ho et al. [12] that show the value of 94.59% covered by the "very high" and "extreme" risk classes. Ribeiro et al. [20] verified that 87.6% of their study area is classified as "high". The primary justification for the similarity of the results is that the different studies were performed in the southern region of Brazil, which consequently presents a predominance of areas with higher altitudes.

The forest fire risk zoning proposed in the present study indicates that the border areas between the municipalities tend to show the "extreme" risk, demonstrating the problem in these regions commonly characterized by wildland-urban interface areas.

There is difficulty characterizing areas of wildland-urban interface related to forest fires in the Brazilian scope, but although incipient, the subject has gained strength in the scientific environment. Although there are different classifications around the globe, local specificities should be considered.

Different studies use similar models of integrating thematic maps in the present research. Batista et al. [4] used three different integration models for the state of Paraná. The authors present in their study the predominance of "moderate" risk in one model and the "extreme" and "high" risks in the other two subsequent models, thus demonstrating the variability of the result based on the information used for integration, as well as on the weights assigned in the weighting model.

Sá et al. [21] used different methods of integrating thematic maps and suggested testing different weights in other studies. Using a distinct weighting model, Mota et al. [18] verify that in Mato Grosso, 55.06% of the area is present from the upper to extreme classes. In contrast, for Kovalsyki et al. [15], the class range is 58.2%, and for Eugenio et al. [8] presents 75% for the state of Espirito Santo. These values are higher than in the present study, but there is a distinction in the variables and weights that make up the integralization model used.

Companies, both public and private, employ various methodologies for automating fire risk classification. A notable example is proposed by the National Institute of Space Research (INPE). According to Setzer et al. [23] this methodology is based on the meteorological principle that the longer a specific area goes without rain, the higher its risk of vegetation burning. Additionally, INPE's model incorporates additional variables such as vegetation type, maximum daily temperature readings, minimum relative air humidity levels, topographic elevation, magnitude of latitude, the presence of fires in close proximity to evaluate fire risks more precisely.

The automation of fire risk classification evolves the methodology presented in this study by incorporating variables with daily variability related to vegetation fires.

Comparations between research that used different methodologies and study areas do not present as much effectiveness as testing the very efficiency of the proposed zoning. Thus, by demonstrating the predominance of fires that occurred from 2011 to 2016 in "very high" and "high" risk classifications, it is verified that the proposed zoning is satisfactory for the study area.

5 Conclusion

Based on the results obtained, we concluded that:

- The integration of the different thematic maps generating the forest fire risk zoning for the metropolitan region of Curitiba presented a satisfactory efficiency,

being able to be used for the management of prevention politics, aiming at the minimization of the damages caused by the fires.
- It is recommended to evaluate the optimization of forest fire risk zoning incorporating meteorological variables and urban characteristics since there are variables not covered by this and another manuscript that may present greater refinement and consequently better efficiency in future risk zoning.

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H.R. Ferreira, is a Forestry Technician in 2008 from the Colégio Florestal Estadual Presidente Costa e Silva, Brazil. BSc. Eng. in Forestry Engineer in 2017, from the Federal University of Paraná (UFPR) Brazil, and BSc. Eng. in Occupational Safety Engineer on 2021, from the UNIFACEAR. Sp. in Forest Fire Prevention in 2021, from the UFPR and a MSc. in Nature Conservation in 2021, from the Postgraduate Program in Forestry Engineering at UFPR, Brazil. He has been a doctoral candidate in the area of Nature Conservation through the Postgraduate Program in Forestry Engineering at UFPR, where he has dedicated himself to academic research related to fires in vegetation located in wildland-urban interface areas, acting as an ad hoc reviewer of journals. He has experience carrying out different works in the forestry area and currently holds the position of forestry engineer at Itaipu Binacional with the Protected Areas Division (MARP.CD).
ORCID: 0000-0002-9433-6757

A.C. Batista, graduated in 1979, MSc. in 1984 and Dr. in Forestry Engineering in 1995 from the Federal University of Paraná, Brazil. He is currently a full professor at the Federal University of Paraná. He has experience in the area of Forest Resources and Forest Engineering, with an emphasis on forest protection and meteorology and forest climatology,

working mainly on the following topics: preventing and combating forest fires, fire behavior, fire effects, controlled burning, microclimate, urban climate and urban-rural interface (WUI). He is a professor at the Postgraduate Program in Forestry Engineering at the Federal University of Paraná and the Postgraduate Program in Forestry and Environmental Sciences at the Federal University of Tocantins. Since April 2016, he has been editor-in-chief of Revista Floresta. He is currently the Coordinator of the Postgraduate Program in Forestry Engineering at the Federal University of Paraná (mandate 07/11/2023-06/11/2025).
ORCID: 0000-0001-5929-3838

A.F. Tetto, is BSc Eng. in Forestry Engineering in 1997from the Federal University of Paraná, Brazil. He specializes in preventing and combating forest fires, with a MSc. and Dr. in Nature Conservation. He served as coordinator of the undergraduate course in Forestry Engineering (2012 to 2014), as Financial Director of FUPEF (Fundação de Pesquisas Florestais do Paraná) (2014 to 2016) and Administrative Director (2019 to 2020). He is currently the financial director of FUPEF, coordinator of the specialization course in preventing and combating forest fires, and associate professor of the Forest Engineering course at UFPR in the disciplines of forest fires, meteorology, and forest climatology and management of wild areas for graduation, and fire ecology, forest microclimatology and management of protected natural areas for postgraduate studies. He works in research with an emphasis on forest fire prevention, microclimatology, and management of conservation units.
ORCID: 0000-0003-2251-964X

D. Biondi, is BSc Eng. in Forestry Engineering from the Federal Rural University of Pernambuco, Brazil. MSc. and Dr. in Forestry Engineering from the Federal University of Paraná. She is currently a full professor at the Federal University of Paraná. She has experience in teaching (undergraduate and postgraduate), research, and extension in the area of forest resources and forestry engineering, with an emphasis on nature conservation. Since August 2014, she has been editor-in-chief of the Journal of the Brazilian Society of Urban Arborization and Deputy Editor of Revista Floresta since July 2016. She coordinates the UFPR Landscaping Laboratory. He has been a Scientific Productivity Fellow at CNPq since 2007. She is currently a member of the Interinstitutional Working Committee of the Public Ministry of Paraná to analyze the Municipal Urban Afforestation Plans of the State of Paraná.
ORCID: 0000-0003-0532-7363