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MULTICRITERIA ANALYSIS FOR IDENTIFYING FOREST FIRE RISK ZONES IN THE BIOLOGICAL RESERVE OF THE SAMA CORDILLERA, BOLIVIA

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KEY WORDS: Protected area, Difference Normalized Burn Index.

ABSTRACT:

Forest fires have negative effects on biodiversity, the atmosphere and human health. The paper presents a spatial risk model as a tool to assess them. Risk areas refer to sectors prone to the spread of fire, in addition to the influence of human activity through remote sensing and multi-criteria analysis. The analysis includes information on land cover, land use, topography (aspect, slope and elevation), climate (temperature and precipitation) and socio-economic factors (proximity to settlements and roads). Weights were assigned to each in order to generate the forest fire risk map. The investigation was carried for a Biological Reserve in Bolivia because of the continuous occurrence of forest fires. Five risk categories for forest fires were derived: very high, high, moderate, low and very low. In summary, results suggest that approximately 67% of the protected area presents a moderate to very high risk; in the latter, populated areas are not dense which reduces the actual risk to the type of events analyzed.

1. INTRODUCTION

Protected areas have an important value for the conservation and preservation of ecosystems within a framework of sustainable development. Management plans of the Biological Reserve of Sama Cordillera in Bolivia (RBCS) indicate that forests at this protected area (PA) are periodically affected by fires of great intensity. As a result, grasslands and rivers are as well affected by the ashes, generating negative impacts on the aquatic flora and fauna. In turn, water pollution can deteriorate the health of the surrounding communities and the population of Tarija city (Artunduaga et al., 2004).

An effective alternative to cope with fires is through prevention (Soares, 1985). For such purposes, it is necessary to identify areas with different degrees of fire risk in order to carry out an effective prevention plan (Andrade et al. 2011), as a countermeasure against fire frequency damage avoidance (Jaiswal et al. 2002). For this reason it is important to find sites with a high risk of forest fires inside the RBCS.

In order to improve risk management measures of forest fires, it is important to understand relevant site factors and its evolution (Tedim, Carvalho, 2013). The use of satellite data to map and identify areas vulnerable to forest fires help to minimize the frequency of fires and thus avoid damage (Jaiswal et al., 2002). Geographic Information Systems (GIS) contribute to associate the variables that integrate the determinants of fire behaviour for the generation of cartographic products useful for forest protection actions and emergency decision making (Andrade et al., 2011).

2. METHODS AND MATERIALS

2.1 Study Area

The RBCS is located in Tarija-Bolivia. It has an area of approximately 1085 km^2. Within the reserve were identified 207 species of birds, 57 species of mammals, 23 species between reptiles and amphibians, 4 species of fish, and 83 species between arthropods, annelids and mollusks.

2.2 Methodology

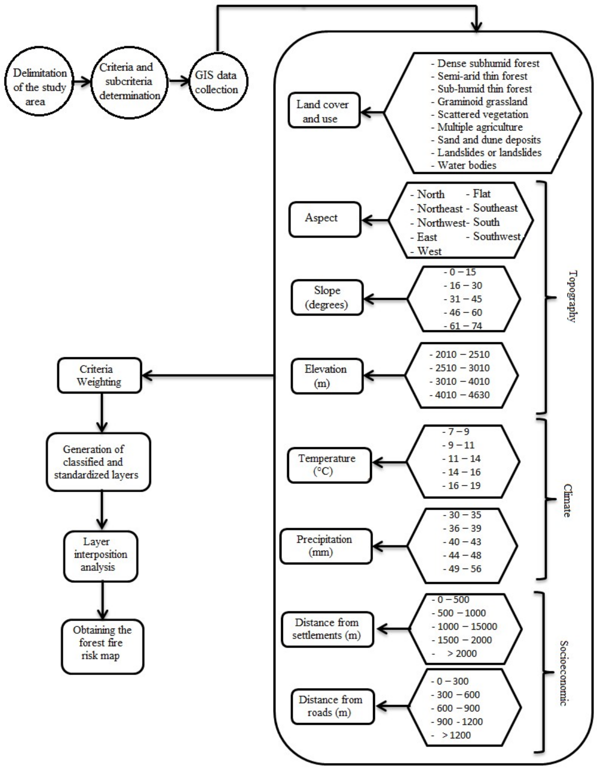

Figure 1. Summary of the methodology

The multicriteria analysis applied is summarized in Figure 1. It gathers concepts, approaches, models and methods, as an aid to decision making based on the description, evaluation, order and

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selection of factors, based on an evaluation. Decisions are taken through evaluations, values or intensities of preference according to various factors, such as objectives, reference values, or usefulness (Moraga, 2010). The analysis can be applied to identify adequate options, classify all alternatives or to evaluate different criteria (Dodgson et al., 2009).

Multicriteria analysis, combined with remote sensing and GIS techniques, is a widely used approach to model forest fire risks (Gigović et al., 2018). The assessment is considered useful due to the fact that it has a visual scope of geographical reference that leads to a comprehensive analysis of elements such as socioeconomic and biophysical factors. Compared to other ground observation systems (such as direct observation or aerial photography), this method provide a global view at different scales which simplifies the analysis of information in regions not visible to the spectrum (Martínez-Vega et al., 2010).

Finally, the Difference Normalized Burn Index (NBR) is used to standardize the final products. The NBR index is used as an additional measure to assess the damage caused by forest fires or to analyse the regeneration capacity and evolution of vegetation after the occurrence of fire events (Bodí et al., 2012). The NBR provides an aid to identify areas with vegetation growth after the fire, areas that were not burned, and areas burned with different levels of severity (Bodí et al., 2012).

2.2.1 Analysis and data interpretation

Data sources

Data was obtained from public access servers. Geo Bolivia (https://geo.gob.bo/portal/) provided most of the data; the projection system is WGS 84. The following data was collected from that mentioned server: National Protected Areas maps (SERNAP, 2014), land use and land cover maps (UTNIT, 2010), road network (ABC, 2017), local communities (INE, 2012). In addition, the 30 m resolution Digital Elevation Model corresponds to NASA´s Shuttle Radar Topography Mission (Rodriguez et al., 2006) (https://lpdaac.usgs.gov/tools/earthdata-search/), temperature and precipitation from year 2000 correspond to the Geospatial and Farming Systems Consortium Server, WorldClim – Global Climate Data (Fick, Hijmans, 2017). Regarding satellite imagery, it correspond to Landsat 8 July 26th and August 25th, 2017, May 21st and July 2nd, 2019, obtained from Earth Engine platform.

Land cover and land use

It is one of the most important parameter affecting fire occurrence and fire spread (Rather et al., 2018). Within this element, classification was accomplished according to its flammability and vulnerability to fires; classes were weighted according to Chavan et al. (2012).

Soil information was classified within a range of 1 to 5, according to the forest fire vulnerability level (Table 1; Figure 2). Thus, a weight of 5 was assigned to forested vegetation due to the high risk to fire in comparison to other types of vegetation, such as thickets, grasslands or pastures (Rather et al., 2018); likewise, forests grasslands and non-dense vegetation have a weight of 4, agricultural areas have a weight of 3, and drier areas (which include sand, dunes and erosive areas) have a weight of 2 because of the low risk to fires; water bodies have a value of 1 (Luiz de Sá de Oliveira, 2013).

Classes	Weight	Classification
Water bodies	1	Very low
Sand and dune deposits; landslides	2	Low
Agriculture	3	Moderate
Grassland; scattered vegetation	4	High
Dense sub humid forest; semi-arid thin forest; sub-humid thin forest	5	Very high

Table 1. Land cover and land use weighting

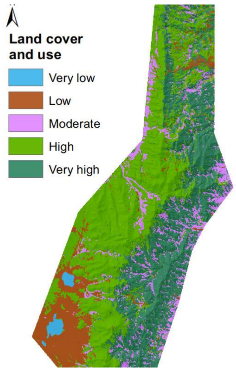

Figure 2. Weighted land use-land cover map

Climate

The relationship between climate and forest fires is based on the moisture content of soil and vegetation (Muñoz et al. 2005). Although fires can occur at any temperature, their frequency has a certain level of dependence on temperature increase or reduction (Gigović et al., 2018). High temperatures lead to dry vegetation, which imply higher risk to fire (Rather et al., 2018). Precipitation is an important factor as well, due to the influence it has on the humidity of the air, habitat and flammability; the ignition capacity of a sector can vary based on the moisture in the atmosphere due to precipitation. A wet medium has higher influence at the beginning of a fire event and the spread of fire; on the other hand, if soils or vegetation are dry, fire will spread faster. With this criterion, annual average values of temperature and precipitation were classified in five ranges and weighted according the vulnerability level to fires (Table 2). Figure 3 displays the mapped criteria.

Classes		Weight	Classification
Precipitation (mm)	Temperature (°C)		
49 – 56	7 – 9	1	Very low
44 – 48	9 – 11	2	Low
40 – 43	11 – 14	3	Moderate
36 – 39	14 – 16	4	High
30 – 35	16 – 19	5	Very high

Table 2. Weighting for climate data

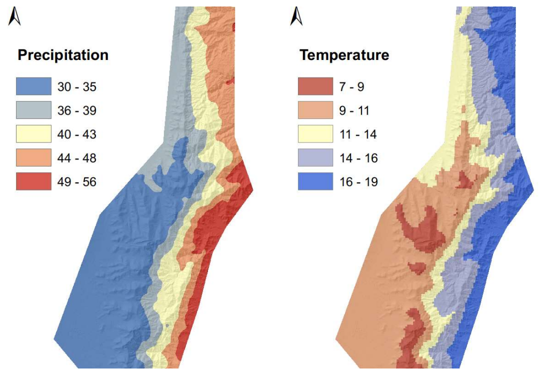

Figure 3. Weighted climate maps

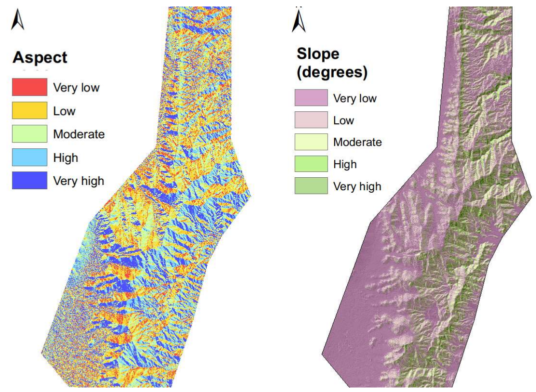

Figure 4. Weighted maps of aspect and slope

Topography

Topography is related to wind, sun exposure and humidity, because of which it should be expected an influence on fire spreading (Jaiswal et al., 2002). Three sub-criteria were considered: aspect, slope and elevation. Aspect influences solar radiation intensity that reaches the ground, in turn affecting air humidity and the flammability of the available matter (Luiz de Sá de Oliveira, 2013); aspect also provides a relationship between terrain, sunlight and wind (Jaiswal et al., 2002). Slope influences forest fires as it affects the spread of fire (Adab et al., 2011); the highest the slope, the more the flames bend and the fire area expands (Luiz de Sá de Oliveira, 2013). Elevation is associated with wind trends, temperature, precipitation and the spread of fire (Gigović et al., 2018; Rather et al., 2018); it influences vegetation, the humidity of the material and air humidity, for instance it is of interest for the kind risk being analysed (Adab et al., 2011). As a result, five vulnerability levels were weighted for aspect based on Gigović et al. (2018); slope and elevation were weighted on five levels as well, based on the vulnerability (Table 3; Figure 4).

Classes			Weight	Classification
Aspect	Slope (degrees)	Elevation (m)		
North	0 – 15	4010 – 4630	1	Very low
Northeast; Northwest	16 – 30	3510 – 4010	2	Low
East; West	31 – 45	3010 – 3510	3	Moderate
Southeast	46 – 60	2510 – 3010	4	High
South; Southwest	61 – 74	2010 – 2510	5	Very high

Table 3. Weighting according to the topographic data

Socioeconomic factors

The proximity to settlements is important since human activities are often related to fire occurrence (Chavan et al., 2012; Gigović et al., 2018; Rather et al., 2018). Roads which cross forested areas are useful for fire fighting because they facilitate access to firemen equipment, which accelerates the process of fire control, minimizing the damage caused (Martell, 2007). Nevertheless, the accessibility of humans to areas near roads causes them to be a cause of fire occurrence due to the influence of anthropogenic activities (Gupta, Nair, 2012). In turn, the air flow created by vehicular circulation is another factor likely to increase the spread of fire (Rather et al., 2018).

For the analysis, buffer distances were considered for roads and settlements, which led to five distance ranges. According to that criteria (i.e., the closer distances have a higher risk level), the weighs considered are described in Table 4. Figure 3 presents maps constructed under the criteria referred to aspect, elevation and distance from settlements.

Classes		Weight	Classification
Distance from roads (m)	Distance from settlements (m)		
> 1200	> 2000	1	Very low
900 – 1200	1500 – 2000	2	Low
600 – 900	1000 – 1500	3	Moderate
300 – 600	500 – 1000	4	High
0 – 300	0 – 500	5	Very High

Table 4. Weighting for socioeconomic data

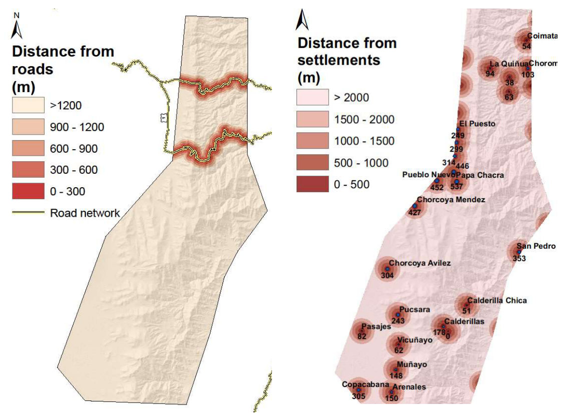

Figure 5. Weighted socioeconomic maps

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2.2.2 Sub criteria integration

In order to determine the risk of forest fires, the sub criteria described in previous paragraphs were integrated through the valuation assigned to each one. Map algebra was used to sum up the sub-criteria according to their corresponding risk percentage. Next, the resulting map was standardized to construct forest fire risk maps. The weighting values shown in Table 5 follow the criteria of Gigović et al. (2018). Resulting maps are presented in Figure 4.

Criteria	Sub criteria	Weight
Topography	Aspect	0.623
	Slope	0.239
	Elevation	0.138
Climate	Temperature	0.750
	Precipitation	0.250
Socioeconomic	Distance from settlements	0.250
	Distance from roads	0.750

Table 5. Weights for sub criteria integration

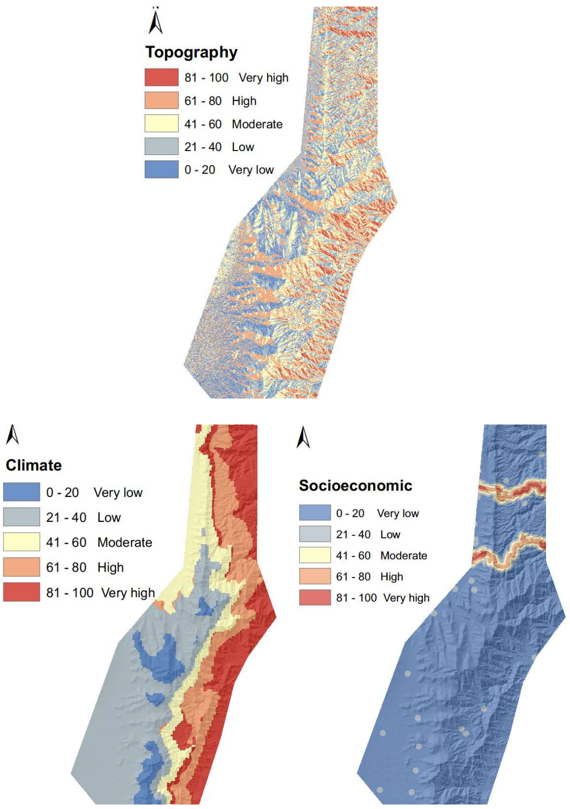

Figure 6. Maps of sub criteria integration

3. RESULTS AND DISCUSSION

Table 6 shows the weighting criteria used in the generation of the forest fire risk map. All values were assigned according to Gigović et al. (2018). The highest weights were assigned to land use and land cover because they define the flammability of the material. The next level corresponds to the socioeconomic criteria, due to its high influence on fire ignition after the potential impacts of human behaviour. The topographic and climate criterion define the next levels. Then, to obtain the final forest fire risk map, all the criteria were integrated based on their weighting, resulting in the map shown in Figure 5. Table 6 and Table 7 show the risk classification used in the final map.

Criteria	Weight
Land cover and use	0.450
Socioeconomic	0.321
Topography	0.142
Climate	0.087

Table 6. Criteria weights for fire risk map

Classification	Area (Km^2)	Area percentage (%)
Very low	79.4	7
Low	270.2	25
Moderate	561.3	52
High	162.7	15
Very high	11.2	1

Table 7. Fire risk areas

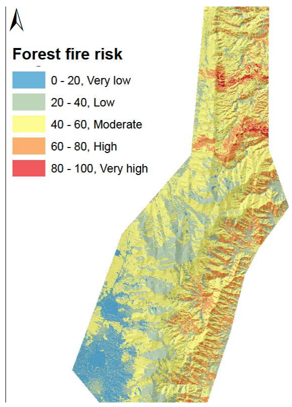

Figure 7. Forest fire risk map

3.1 NBR

An additional classification was applied to determine if areas previously affected by fires coincide with the areas that were estimated to have high risk to forest fires (Table 8). The superposition of the NBR index map to the forest fire risk map (Figure 6), identifies NBR areas which intersect with the fire risk levels. Resulting maps shows that the most significant fires occurred within the study area in years 2002, 2017 and 2019.

Range	Classification
< (- 0.25)	High growth of vegetation after fire
(-0.25) to (-0.10)	Low growth of vegetation after fire
(- 0.10) to 0.10	Stable or unburned areas
0.10 to 0.27	Burned areas with low severity
0.27 to 0.44	Burned areas with moderate to low severity
0.44 to 0.66	Burned areas with moderate to high severity
> 0.66	Burned areas with high severity

Table 8. NBR Index values

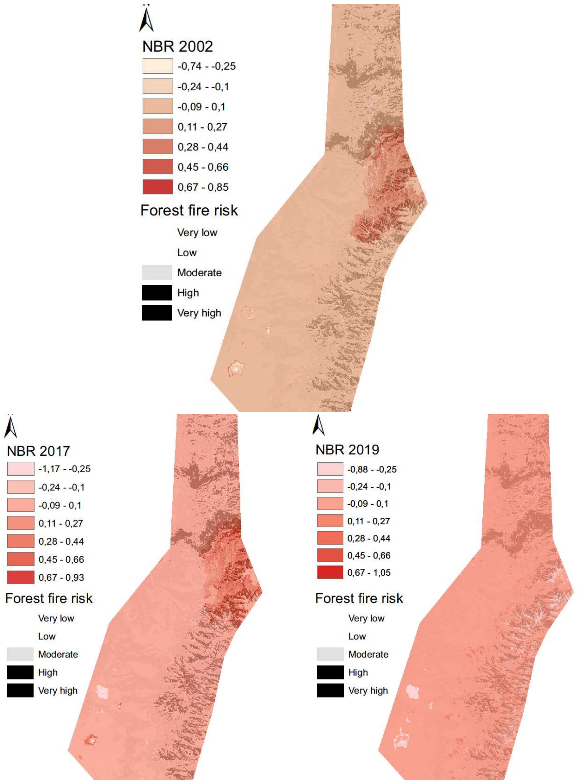

Figure 8 (continuation). NBR index and forest fire risk maps

3.2 Risk of communities to forest fires

Classification	Community	Population
Low risk	Calderilla Chica	51
	La Quiñua	94
	Choroma	103
	Muñayo	148
	Arenales	150
	Pucsara	243
	Copacabana	305
	TOTAL POPULATION	1094
Moderate risk	Calderilla grande	0
	Cochas	38
	Vicuñayo	62
	Tres morros	63
	Pasajes	82
	Puesto grande	101
	Calderillas	178
	El puesto	249
	Chorcoya Avilez	304
	Chilcayo	314
	San Pedro de Sola	353
	Chorcoya Mendez	427
	Papa Chacra	446
	Pueblo Nuevo	452
	Quebrada grande	537
	TOTAL POPULATION	3606
High risk	Coimata	54
	Sama	299
	TOTAL POPULATION	353

Table 9. Population of communities within each risk level areas

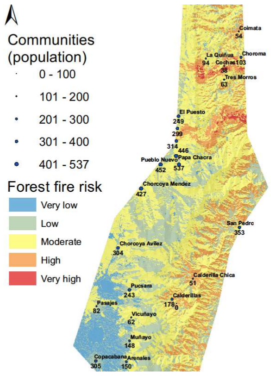

Figure 9. Communities and forest fire risk map

Population data from the National Census of year 2012 was carried in order to obtain an approximate data of the population in 2018. The aim was to estimate the population which live in the different levels of fire risk inside the RBCS. The calculated averages are shown in Table 9 and Figure 7.

4. CONCLUSIONS

The forest fire risk map shows that high and very high risk levels exist in 16% of the total RBCS area. On the other side, most of the surface has a moderate level of risk (52% of the area). Although the surface area seems small in value, it should be considered that those zones are very close to the sectors which present a high or very high level of risk, which implies that they can also be harmed since they have similar characteristics.

When performing maps superposition, the areas with high growth of vegetation after the fire occurrence are located nearby the areas with a high level and very high risk of forest fires. In turn, it can be noted that burned areas with high severity are located nearby areas with a moderate and high level of risk.

Based on the comparison of communities inside the RBCS and the forest fire risk map, it can be determined that nearby areas with very high risk and very low risk, few settlements are found. It was also determined that approximately 1094 people live in low risk areas; however, most of the settlements of the RBCS are located in areas with a moderate fire risk. In areas with a higher level of risk, there are only two populations with a total of 353 residents.

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