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LEARNING TO COEXIST WITH WILDFIRES: RELATIONSHIP BETWEEN FIRE, LANDSCAPE AND POPULATION

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1 INTRODUCTION

Fires are common disturbances, occurring naturally ignited or lightning, intentionally or accidentally by people. Everyday thousands of hectares of forests, woodlands, savannas, grasslands, shrublands, tundra, wetlands, and agricultural fields burn on the entire Earth (except Antarctica). For both people and ecosystems, fire can be harmful or beneficial depending on where, when, and how it burns. Fire can be harmful mainly in ecosystems composed of plants and animals with a lack of adaptations to withstand or take advantage of it. Most of the natural burned area occurs in grasslands and savannas where fires maintain open landscapes by reducing shrub and tree cover (SCHOLES; ARCHER, 1997; ABREU et al., 2017; SILVA-JUNIOR et al., 2020).

Paleoclimatic and paleobotanic records prove the presence of natural burning regimes in the evolution of terrestrial ecosystems long before the emergence of humans, with their origin linked to the emergence of plants, nearly 420 million years ago (SCOTT; GLASSPOOL, 2006). The emergence and expansion of human civilization consolidated as the main source of fire ignitions on the Earth, resulting in a significant alteration of the natural fire regimes (PAUSAS; KEELEY, 2009). In addition, the landscape changes promoted by human activities are increasing its conditions of fire susceptibility, materialized mainly by the construction of new road networks and the advance of agricultural frontiers, with the removal of natural vegetation, the introduction of invasive species and use of fire as a tool for agriculture practices (FOLEY et al., 2005).

In general, fires can affect the distribution of global ecosystems (BOND et al., 2005), reducing plant biomass and changing the structure of vegetation communities (VEENENDAAL et al., 2018). Also, fires are dynamic ecological forces that have evolutionary consequences and are fundamentally shaped by human actions (MCLAUCHLAN et al., 2020), causing disturbances on soil's chemical composition, carbon and water cycles, as well as, the climate system through the release of greenhouse gases (WERF et al., 2004; WERF et al., 2010; ARAGAO et al., 2018).

In some future scenarios, land use change, dry season, burned area and carbon emissions are projected to increase in all Shared Socioeconomic Pathways (SSP) scenarios, driven by an increase in temperature and a decrease in moisture availability, as well as, increase in food production and use of bio-fuels (LI et al., 2017; BURTON et al., 2020; BURTON et al., 2022).

The ecosystems differ in their response and susceptibility to fire events, where the impacts of changes in fire regimes reach different levels according to the characteristics of a particularly affected ecosystem. Conforming to ecological terms this is closely related to the way in which a given landscape has historically evolved with fire (ALVES; ALVARADO, 2019). Ecosystems characterized by the dominance of grasses, for instance, are co-evolved with fire, where their plants and animals show several adaptations and synergies with it. On the other hand, tropical forests are not fire-adapted and do not easily burn unless they suffer extreme drought or degradation/deforestation. When forests burn, fire can cause extremely negative effects on their biodiversity (PIVELLO et al., 2021). Fire impacts in a given ecosystem are determined by fire regime, the pattern of fire type, frequency, seasonality, intensity, and extent (JURVELIUS, 2004; KEANE, 2013).

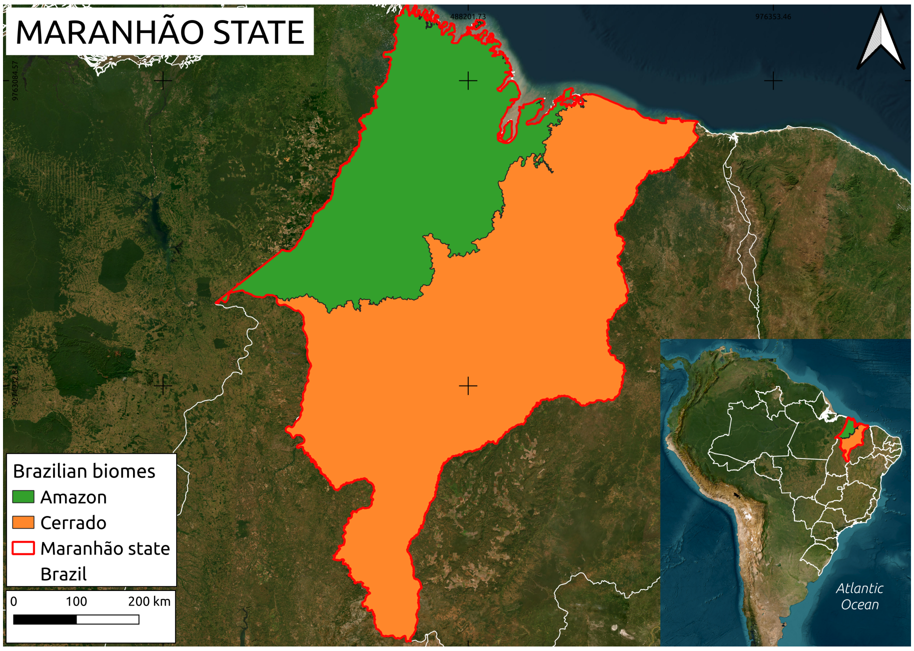
In this sense, this research aimed to investigate the relationship between fire patterns, landscape and population in the Maranhão state for 2016, a year of extreme weather (El Niño).

2 MATERIALS AND METHODS

2.1 Study Area

The study area corresponds to Maranhão state (Figure 2.1), located in northeast portion of Brazil, characterized by a territorial area of 329,651.5 km^2; a total population of 7,153,262 hab and by a presence of two biomes: Amazon (35%) and Cerrado (65%).

Figure 2.1 - Study Area - Maranhão state.



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2.2 Data Collection

Three datasets were used for the research analysis:

1. Burned Area, collected from Global Fire Atlas, a freely available dataset for the period between 2003 and 2018, that tracks the daily dynamics of individual fires to determine the timing and location of ignitions, fire size and duration, daily expansion, fire length, speed, and direction of spread (ANDELA et al., 2019).

2. Land Use and Land Cover (LULC), extracted from MapBiomas Collection 7, annual historical maps of LULC (1985-2021), based on random forest applied to

Landsat archives using Google Earth Engine (SOUZA et al., 2020).

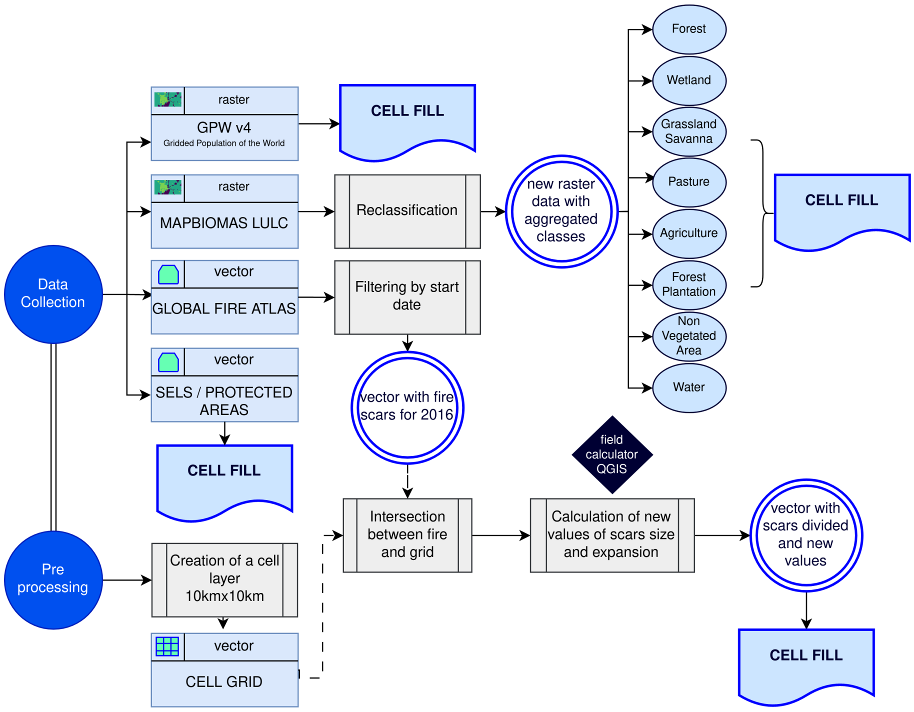
3. Population density, extracted from Gridded Population of the World (GPW v4), models which combines national population census to provide the distribution of human population (counts and densities) on a continuous global raster surface.

2.3 Methodological Procedures

After a data collection step, a regular grid of size 10 km^2 was created to perform the cell filling (pre-processing). The main goal of this process is to homogenize information from different datasets sources, aggregating on a same spatial-temporal base. The fire data was filtered according to the start date, separating the fire polygons to 2016 year and resulting in one shapefile for the year. Aiming to fill the information correctly, an intersection step between fire and grid was performed to divide the polygons according to each cell.

Still in the pre-processing step, we performed a reclassification process to aggregate the land use and land cover classes according: Forest (Forest Formation, Sandy Coastal Plain Vegetation), Wetland (Mangrove, Wetland, Hypersaline Tidal Flat), Grassland/Savanna (Savanna Formation, Grassland, Rocky Outcrop, Herbaceous Sandbank Vegetation, Other non Forest Formations), Pasture, Agriculture (all crop uses), Forest Plantation, Non Vegetated Area (Beach, Dune and Sand Spot, Urban Area, Mining, Other non Vegetated Areas) and Water (River, Lake and Ocean). Forest, Wetland and Grassland/Savanna were grouped as natural vegetation (Figure 2.2).

Figure 2.2 - Methodological Procedures - Step 1 (Data Collection and Pre-processing).



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We defined three dimensions to work: fire; landscape; population and terrestrial management.

Concerning the first one, fire dimension, we aggregated to the grid some fire metrics: fire size (km^2); duration a fire (days); fire expansion (km^2/day); fire speed (km/day) (Table 2.1). We adopted some premises for each fire metric: size (higher values mean greater fire extension); duration (the longer the duration of the fire, the greater the impacts on the environment); expansion (higher values mean faster fire spread); speed (higher speed means more severe fires).

Table 2.1 - Description of the fire metrics calculated.

Fire metric	**Unit**	**Description**
Size	km^2	Total burned area in each cell (sum)
Duration	days	Average of fire duration in each cell (mean)
Expansion	km^2/day	Average of daily fire expansion in each cell (mean)
Speed	km/day	Average of fire speed in each cell (mean)

Landscape ecology involves the study of landscape patterns, the interactions among patches within a landscape mosaic, and how these patterns and interactions change over time. We extracted some landscape metrics (Table 2.2), using the landscape metrics package, available in Rstudio (https://cran.r-project.org/web/packages/landscapemetrics/index.html). In this sense, we used a binary reclassification between Natural Vegetation and Non Natural Vegetation and, calculated the landscape metrics for the Natural Vegetation class. These metrics were calculated for 2016 and aggregated to the grid. Also, we adopted some premises: PLAND and CA (the larger the area and percentage of natural vegetation, the more biomass will be available for burning); NP and ED (the greater the level of landscape fragmentation, the greater the influence of external factors and, therefore, the greater the susceptibility of the area to fires occurrence).

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o que é sua unidade de paisagem??

Table 2.2 - Description of the landscape metrics calculated.

Scale	**Acronym**	**Metric**	**Unit**
Class	PLAND	Percentage of Natural Vegetation	%
Class/landscape	NP	Number of Natural Vegetation Patches	count
Class/landscape	ED	Natural Vegetation Edge Density	m/ha
Class/landscape	CA	Total Natural Vegetation Area	ha

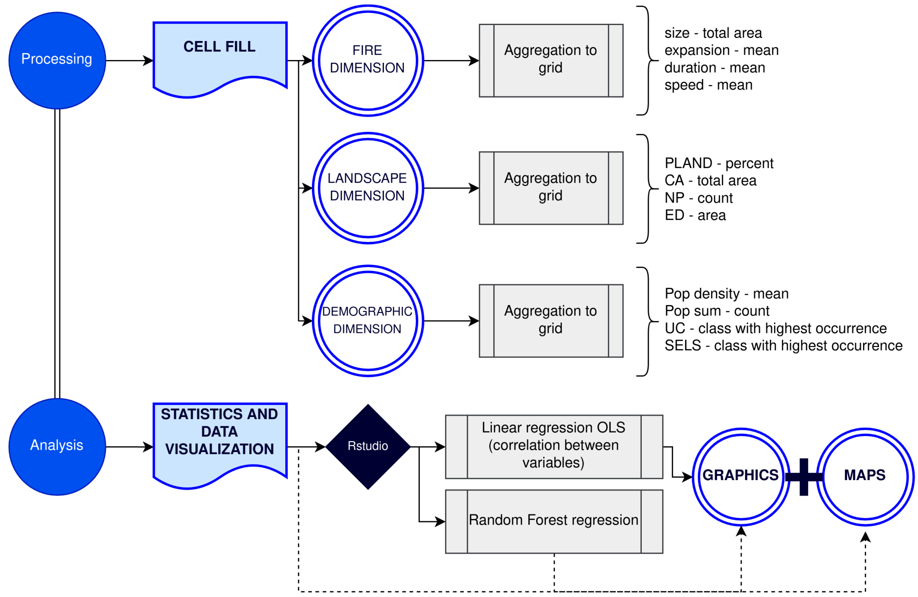
Regarding the third and last dimension, population and terrestrial management, we aggregated to the grid the population count and density; and Social-Ecological systems (SELS) and Protected Area types (Table 2.3). The premises adopted were: population (the increase of humans in the Earth intensified ignition sources and changed vegetation. The impact of increasing human-population density on burned area is generally negative); Protected Area (we divided in some categories: No protected Area; Indigenous Lands; Sustainable Use; Integral Protection); SELS type (A4 - low diversity; low populated shrubby lands; C2 - consolidation of agricultural lands in savannas; D3 - highly populated and biodiverse historical semi-arid areas; E1 - south american lowlands, new agropastoral frontiers; E3 - tropical forests with low anthropogenic conversion).

Finally, to analyze the relationship between variables we applied two statistical models: a liner regression (Ordinary Least Squares - OLS) and a random forest regression (with 2000 trees) (Figure 2.3).

Table 2.3 - Description of the population and terrestrial metrics calculated.

Metric	Unit	Description
Population count	count/pixel	Total number of persons per cell (sum)
Population density	count/km^2	Average of number of persons per km^2 in each cell (mean)
SELS type	-	SELS type with the highest occurence in the cell
Protected Area	-	PA type with the highest occurence in the cell

Figure 2.3 - Methodological Procedures - Step 2 (Processing and Analysis).



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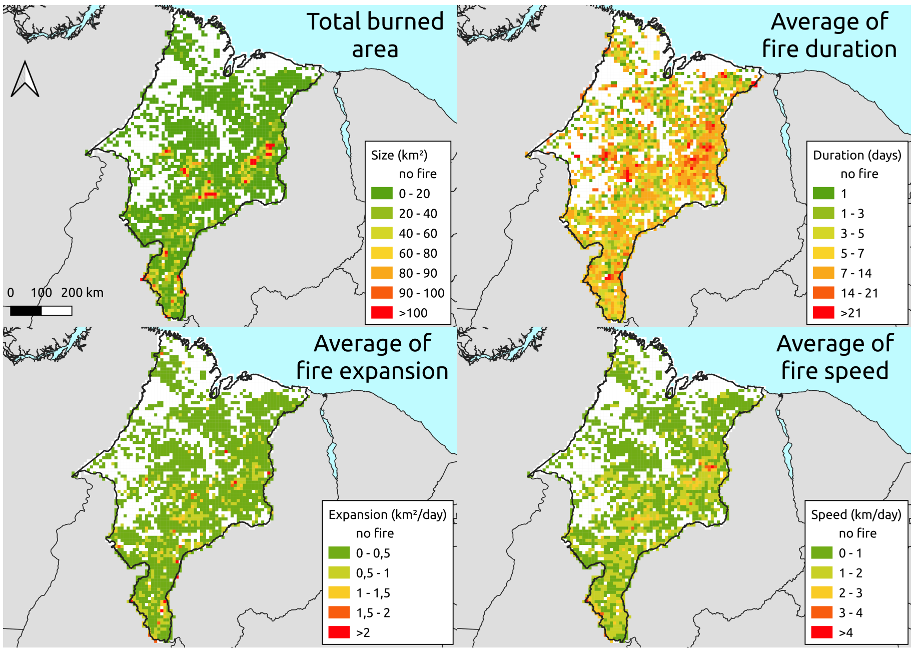
3 RESULTS AND DISCUSSION

We divided the results into three sections: fire dimension; landscape dimension and population and terrestrial management dimension.

3.1 Fire Dimension

Fires are characterized by their intensity, the frequency with which they occur, the season in which they occur, their spatial pattern or extent, and their type. Combined, these attributes describe the fire regime. In general, we observed a concentration of burned area and a fire more severe in the central and east portion of the Maranhão territory (Figure 3.1 and Table 3.1). In addition, concerning the relationship between fire metrics we observed a highest r-squared in the Random Forest Regression and a proportional relationship between size, duration, expansion and duration (Figure 3.2 and Figure 3.3).

Figure 3.1 - Fire dimension: spatial fire patterns in the Maranhão state.



Source: created by the author.

Table 3.1 - Proportion of cells per class for fire dimension in the Maranhão state.

Size	Duration	Expansion	Speed
0 (39.5%)	0 (38.8%)	0 (43.4%)	0 (38.8%)
0-20 (48.4%)	0-1 (6.9%)	0-0.5 (49.4%)	0-1 (43.4%)
20-40 (6.2%)	1-3 (7.7%)	0.5-1 (5.7%)	1-2 (15.6%)
40-60 (3.1%)	3-5 (12.5%)	1-1.5 (0.9%)	2-3 (2%)
60-80 (1.3%)	5-7 (11.2%)	1.5-2 (0.3%)	3-4 (0.3%)
80-90 (0.4%)	7-14 (19.1%)	>2 (0.2%)	>4 (0.06%)
90-100 (0.4%)	14-21 (3.9%)		
>100 (0.7%)	>21 (0.8%)		

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Figure 3.2 - Fire dimension: relationship between variables using OLS model.

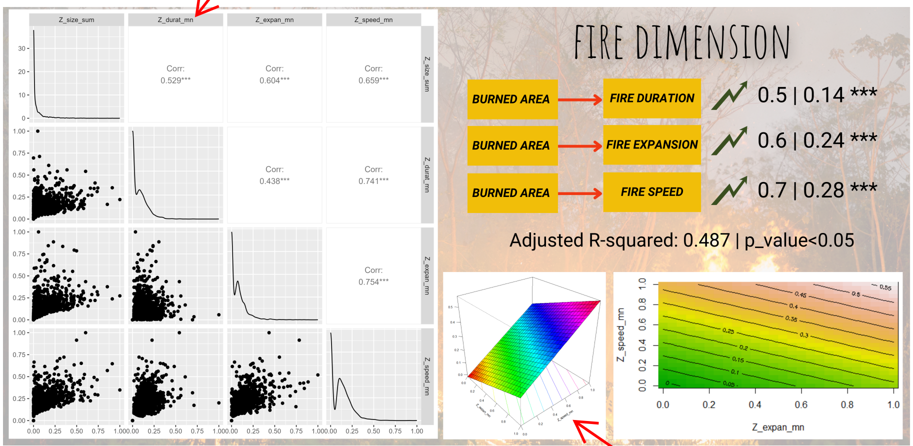

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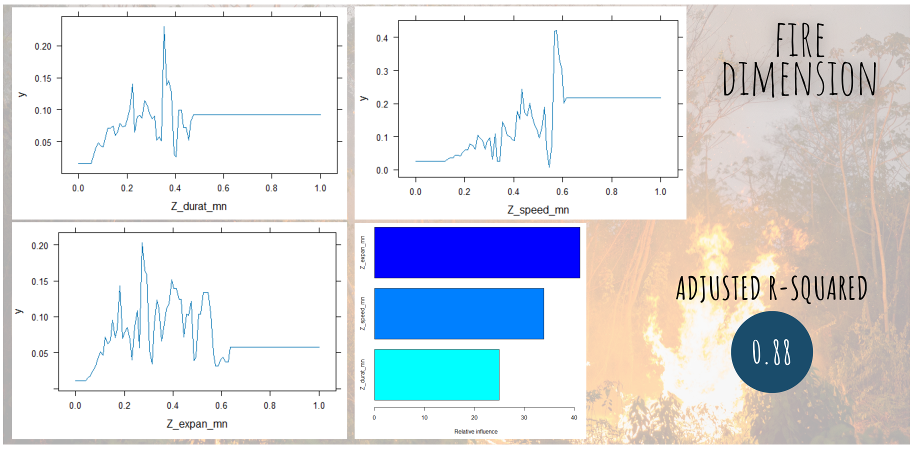
Figure 3.3 - Fire dimension: relationship between variables using Random Forest regression model.

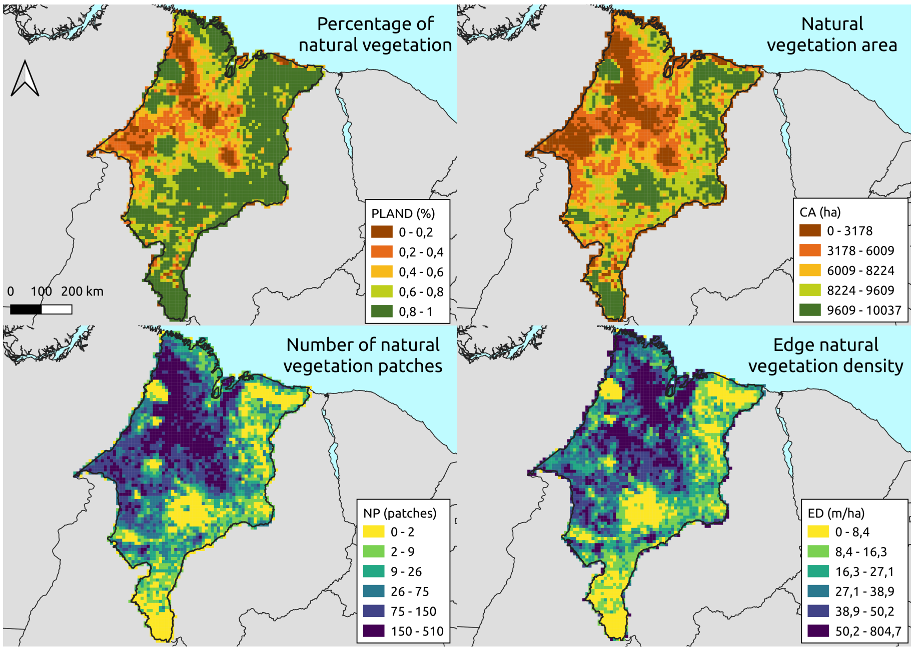


Source: created by the author.

3.2 Landscape Dimension

An intense process of degradation and losses of original coverage was observed due to the expansion of agricultural and pasture areas, contributing to an increase in fire occurrence. In the case of landscape patterns, high levels of fragmentation are concentrated in the central and north portion of the Maranhão territory (Figure 3.4 and Table 3.2). In addition, concerning the relationship between fire and landscape metrics, also, we observed a highest r-squared in the Random Forest Regression, a proportional relationship between fire, PLAND and CA, and a behaviour inversely proportional between fire, NP and ED (Figure 3.5 and Figure 3.6).

Figure 3.4 - Landscape dimension: spatial landscape patterns in the Maranhão state.

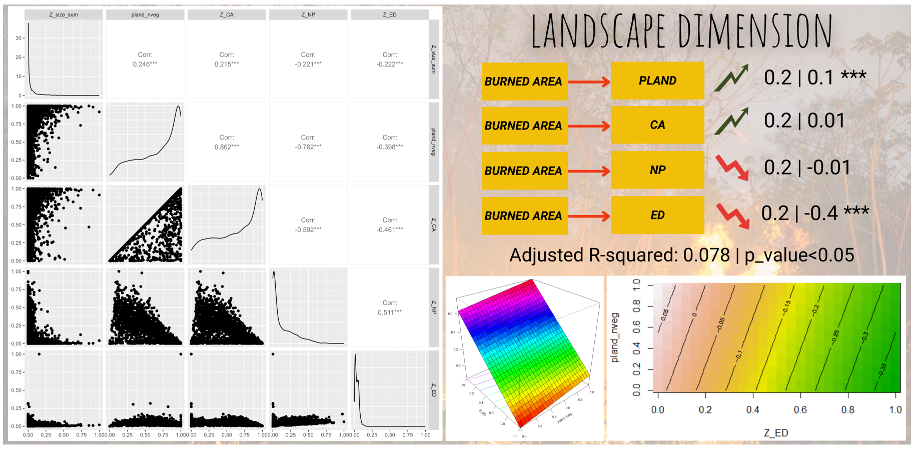


Source: created by the author.

Table 3.2 - Proportion of cells per class for landscape dimension in the Maranhão state.

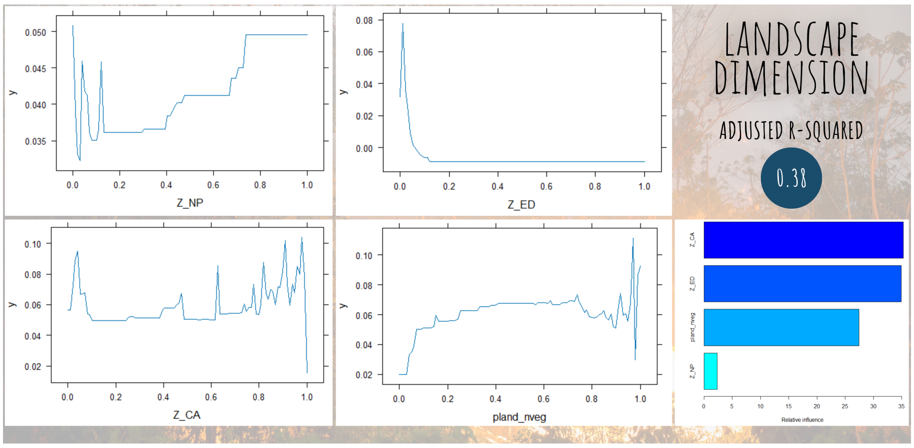
PLAND	CA	NP	ED
0-0.2 (13.5%)	0-3178 (20.02%)	0-2 (17.66%)	0-8.4 (17.13%)
0.2-0.4 (12.6%)	3178-6009 (19.99%)	2-9 (16.93%)	8.4-16.3 (16.37%)
0.4-0.6 (15.5%)	6009-8224 (19.99%)	9-26 (15.47%)	16.3-27.1 (16.62%)
0.6-0.8 (24.1%)	8224-9609 (20.02%)	26-75 (16.71%)	27.1-38.9 (16.62%)
0.8-1 (34.3%)	9609-10037 (19.97%)	75-150 (16.76%)	38.9-50.2 (16.68%)
		150-510 (16.46%)	50.2-804.7 (16.57%)

Figure 3.5 - Landscape dimension: relationship between variables using OLS model.



Source: created by the author.

Figure 3.6 - Landscape dimension: relationship between variables using Random Forest regression model.



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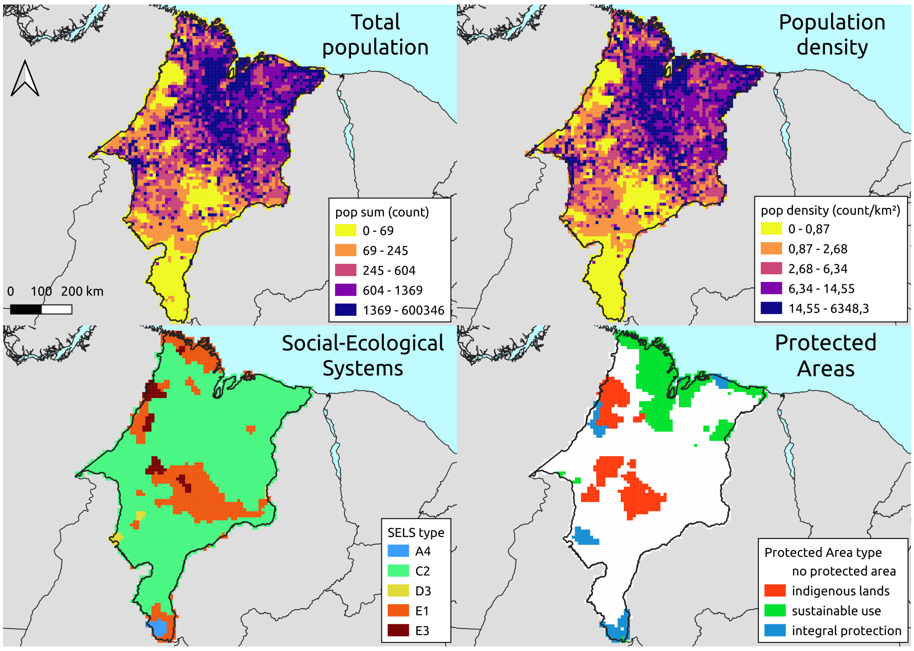
3.3 Population and Terrestrial Management Dimension

We observed that protected areas of Sustainable Use and Indigenous Lands have been threatened by fire events and fire occurs, mainly, in the areas of consolidation of agricultural lands in savanna portion (Figure 3.7 and Table 3.3). In addition, high concentration of population is observed in the central and north portion of the Maranhão territory. Concerning the relationship between fire and population, we observed, also, a highest r-squared in the Random Forest Regression, and a proportional behaviour between fire and population (Figure 3.8 and Figure 3.9).

Figure 3.7 - Population and terrestrial management dimension: spatial population, Socio-Ecological Systems and Protected Areas patterns in the Maranhão state.



Source: created by the author.

Table 3.3 - Proportion of cells per class for population and terrestrial management dimension in the Maranhão state. IL = Indigenous Lands; SU = Sustainable Use; IP = Integral Protection.

Pop count	Pop density	SELS	PA
0-69 (20.05%)	0-0.87 (20.30%)	A4 (0.79%)	None (70.57%)
69-245 (20.05%)	0.87-2.68 (19.74%)	C2 (77.17%)	IL (10.28%)
245-604 (19.97%)	2.68-6.34 (19.97%)	D3 (0.76%)	SU (14.97%)
604-1369 (19.97%)	6.34-14.55 (19.99%)	E1 (18.51%)	IP (4.18%)
1369-600346 (19.97%)	14.55-6348.3 (19.99%)	E3 (2.72%)	

Figure 3.8 - Population and terrestrial management dimension: relationship between variables using OLS model.

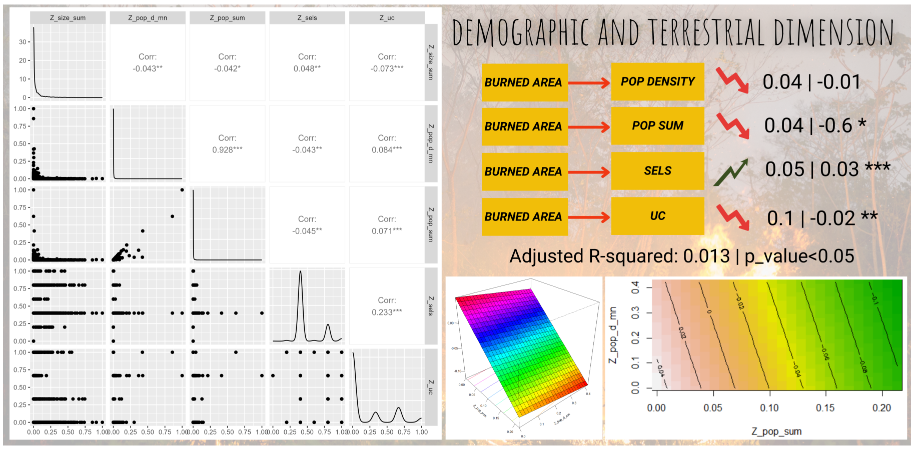


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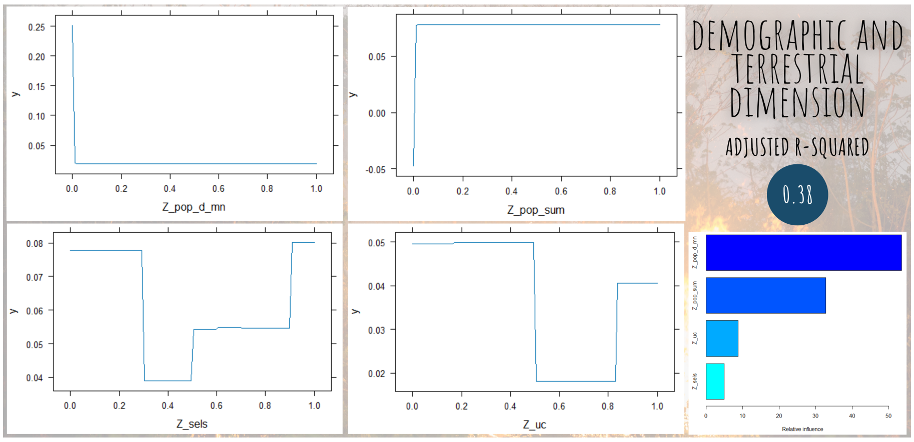
Figure 3.9 - Population and terrestrial management dimension: relationship between variables using Random Forest regression model.



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3.4 Final Considerations

Wildfires are among the greatest forms of disturbance in tropical ecosystems, making the areas more favourable for landscape changes like pasture transformation and advancement of the agricultural frontier. Land use and land cover changes (LULCC) can affect climate through changes in moisture and energy budgets, which is directly associated with deforestation of the Amazon forests. Its clear that non-Amazonian Brazil vegetation has received less attention, despite experiencing the highest transformation rate in the tropics (SALAZAR et al., 2015).

Precolonial pressures in ecosystems were expressed through settlement, cultivation, grazing, hunting and burning by indigenous people, which means temporary changes and, therefore, rapidly were reverted by ecological succession (KNAPP, 2007). Since 1900, due to European exploitation of natural resources, the biomes has been suffered significantly alterations, resulting in widespread transformations (ARMESTO et al., 2010). Global demand for food commodities (e.g. soybeans and beef) has pushed the expansion of agricultural frontier into former natural areas (RICHARDS et al., 2012).

In addition, the use of fire has always been present in human civilizations. The use of fire is culturally framed and transmitted, and it continues to undergo rapid changes in expression (BOWMAN et al., 2011). Understanding the fire regime alteration is crucial, because the survival of many species and ecosystems depends of the historical range of variability in fire activity.

Despite fire occurring naturally in some ecosystems (e.g. savannas and grasslands), over the last two decades, an intense process of degradation and losses of original coverage was observed due to the expansion of agricultural and pasture areas, contributing to an increase in fire occurrence. Naturally, the spatial and temporal patterns of fires can be influenced by ignitions sources like lightning and season. Although, human activities can affect the fire regime in many ways, by changing fuel types, modifying fuel structure and continuity; igniting few or many fires in different seasons under various weather conditions (BOWMAN et al., 2011). One of the human activities is the conversion of natural areas to agricultural or urban use, which is a big problem and intensifies biodiversity loss and climate changes in these regions. In addition, the lack of public policies to combat deforestation can aggravate the biodiversity losses, especially in tropical areas such as the Amazon and Cerrado (BARBOSA et al., 2021; GARCIA et al., 2021; MARTINS et al., 2022; DELGADO et al., 2022).

To further studies is important to consider: i. a time series and other years; ii. more robust methods to data integration (indicators construction); iii. other variables in the economic, social and demographic dimension (e.g. IBGE data); iv.a methodology for characterize social-ecological systems; v. test the methodology in other areas and biomes.

4 CONCLUSIONS

In summary, command-and-control approaches are important and illegal fires need to be prosecuted, but it is also important to actively incentives land users to adopt alternative techniques to fires, such as agroforestry, crop livestock-forest integration, rotation between crop and pasture, no-tillage cultivation, shredding of cut vegetation, and thus allow for a transition to more sustainable and fire-free types of land use. Second, fire management as such can only be efficient if agencies are properly equipped, supplied, and trained; capacity building on the ground and the development of monitoring systems are thus important tasks. Third, research on fire should integrate different knowledge areas from biological to human science in a national research agenda that will create a better basis for developing landscapes that are more resilient to fire. In addition to this, education and outreach are necessary to introduce a deeper understanding on the role of fire to all professionals dealing with natural resources conservation and fire management.

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