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Wildfires as a major challenge for natural regeneration in Atlantic Forest

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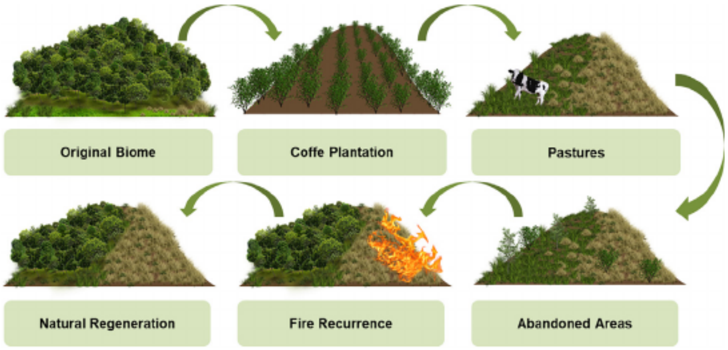
HIGHLIGHTS

- The management of natural regeneration contributes for Atlantic Forest restoration.
- Environmental variables contribute to wildfires and natural regeneration patterns.
- Our results suggest a negative correlation between fires and natural regeneration.
- Slash-and-burn practices inhibit regeneration in areas more exposed to the Sun.
- Fire control is essential for the success of the Atlantic Forest restoration.

GRAPHICAL ABSTRACT



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ABSTRACT

The natural regeneration management is a good strategy of ecological restoration of the Atlantic Forest, one of the most devastated biomes on the planet. However, the frequent occurrence of wildfires is one of the challenges to the success of this method. The objective of this study was to evaluate the effects of wildfires on forest dynamics in Atlantic Forest. The studied area was explored during the coffee cycle when plantations replaced primary forests. We used remote sensing data to analyze the forest dynamics over a period of 50 years (1966–2016). We used the INPE burn database to find the occurrence of hot spots from 1998 to 2016. During this period, we selected the years most affected by the fires for the identification of fire scars using the Normalized Burn Ratio spectral index. From this set of information, we used the methodology of weights of evidence to relate forest dynamics and wildfire events with biophysical and anthropic variables. The results showed that in 1966 the forest area accounted for 8.01% of the land cover, and in 2016 this number rose to 18.55% due to the spontaneous natural regeneration process. The regenerating areas were mainly related to the proximity of the remaining fragments and the portions of the landscape receiving the least amount of global solar radiation. The proximity to urban areas, roads and highways, damaged regeneration and favored both deforestation and wildfire events. Fire scars preferentially occur where there is greater sun exposure. It is possible to observe a negative correlation between the natural regeneration process and the fire scars. We concluded that fire severity is one of the factors that shape the landscape of the region while slowing the regeneration process in preferential areas.

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1. Introduction

The Earth is already in the Anthropocene, an era where *Homo sapiens* records its influence and intervention on the planet (Waters et al., 2016). Several cycles of unsustainable economic exploitation have transformed many biomes in the world and have contributed to climate change. In at least 25 of the so-called global hotspots, the changes are so broad that there is a high risk of extinction of animal and plant species (Myers et al., 2000). To change this, ecological restoration is one of the prime global agendas (Aronson and Alexander, 2013) In 2014, the United Nations Conference on Climate Change (UNFCCC) parties committed through the New York Declaration on Forests to restore 350 million ha by 2030.

There are countless challenges for forest restoration goals to be achieved around the world. This study will address the natural regeneration and wildfire suppression in Atlantic Forest (AF) restoration. The AF is the most altered Brazilian biome, it is estimated that today there is only 12.5% of the original vegetation cover (SOS Mata Atlântica and INPE, 2017).

To mitigate the degradation situation of the biome and to preserve the remaining vegetation, the Brazilian government has adopted policies such as the creation of protected areas and the Atlantic Rainforest Law. Recently, with the approval of the New Forest Code (Law 12.651/2012), the conservation and restoration measures throughout the country have been reformulated. For example, it is necessary to reinstate permanent preservation areas (APP) and legal reservations (RL). Also, non-governmental organizations created the Atlantic Forest Restoration Pact (PRMA) in 2009, aiming to recover 15 million ha by 2050 (Melo et al., 2013).

The achievement of PRMA objective requires a tremendous collective effort. In the AF, active reforestation is very costly, which makes the recovery of large areas unfeasible. Based on previous experiences (Brancalion et al., 2012) estimated an average restoration value of US $ 5000.00 per hectare. As an alternative, the management of spontaneous natural regeneration can generate good results, as observed in some studies (Molin et al., 2017; de Rezende et al., 2015; Teixeira et al., 2009).

However, another challenge for the success of the ecological restoration of the AF is its relationship with fire. Although there are fire-dependent or fire-tolerant biomes (e.g. savannas and grasslands), other types of biomes, such as AF, are fire-sensitive and wildfires constitute a big threat (Hardesty et al., 2005). In fire-sensitive biomes, forest fires are associated with loss of biodiversity, soil degradation, erosion, and reduced water retention (Sansevero et al., 2017; Schmerbeck and Fiener, 2015). Although harmful, the fires occurrence has frequently been happening in AF. In 2017 alone, 19,613 hot spots were registered in the AF area (INPE, 2018). Most of the fires have an anthropic origin, usually associated with slash-and-burn practices (FAO - Food and Agriculture Organization, 2007; Torres et al., 2018).

The success of natural regeneration results from the interaction of several environmental factors (distance from seed source, distance from water bodies, fire recurrence) topographic factors (elevation, orientation, valleys or mountains), and socioeconomic factors (population density, land use and management) (Chazdon and Guariguata, 2016; Molin et al., 2017; de Rezende et al., 2015). Similarly, the landscape characteristics influence the wildfire propagation (Carmo et al., 2011; Torres et al., 2017; Wood et al., 2011). Empirically, one of the responsible factors for AF natural regeneration pattern are wildfires (de Rezende et al., 2015; dos Santos et al., 2016). However, this relationship is not as studied in this biome as in others, such as the Boreal and Mediterranean ecosystems.

In the coniferous forest of the Western Cordillera of Canada and in the tropical forest of Western Tasmania, Australia, fire and topography are responsible for the formation of vegetation islands in places that are called a “fire refugia” by Krawchuk et al. (2016) and Wood et al. (2011), respectively. We believe that this may also be happening with the regeneration of the AF. Understanding the patterns of natural regeneration and their relationship with forest fires in the AF contributes both to the forest recomposition of small areas (recomposition of APP and RL) and to the overall reforestation objective of PRMA.

The main objective of this study was to remotely monitor the relationships between fire occurrence and spontaneous natural regeneration. To achieve this goal we quantify natural regeneration and deforestation occurring in a 50-year interval in an AF area. We also quantified fires and burned area. Then, we evaluated patterns of natural regeneration, deforestation and fire scars in relation to biophysical and anthropic variables. The hypothesis is that wildfire acts as a modeler of the landscape in the AF, difficulting or even preventing regeneration in sites with specific environmental characteristics.

2. Materials and methods

2.1. Study area

The AF is a biome that encompasses a significant portion of the world biodiversity and a large number of endemic species (Myers et al., 2000). Mittermeier et al. (2004) estimated 8000 plants, 148 birds, 71 mammals, 94 reptiles and 286 amphibians of endemic species existing in the AF biome. The AF domain area originally covered around 150 million ha, however this area has been changing from colonization to the present day (Dean, 1996; Ribeiro et al., 2009; SOS Mata Atlântica and INPE, 2017). The AF region bears >72% of the Brazilian population and produces 70% of gross domestic product (GDP). As a consequence, it is estimated that today there is only 12.5% of the original vegetation cover (SOS Mata Atlântica and INPE, 2017) and an intense process of forest fragmentation threats the AF ecosystem (Ribeiro et al., 2009).

The study area (88.172 ha) is located in a seasonal semideciduous forest in the AF domain, between the states of Minas Gerais (MG) and Rio de Janeiro (RJ), in the Southeast of Brazil (Fig. 1). This region is inserted in the morphoclimatic domain known as *mar de morros* (‘sea of hills’) (Ab'Sáber, 1970) characterized by a hill chain whose slopes have rounded shapes. The climatological domain according to the Köppen classification, is the Cwa - subtropical Humid with dry winter (June–September) and hot summer (December–March) (Alvares et al., 2014).The altitude varied between 278 m and 1124 m. The predominant soil class is Red-Yellow Latosol (Lva) (Carvalho Filho et al., 2000).

The region had a traditional economy of gold mining, coffee, and cattle. Coffee plantations replaced the primary forest (Dean, 1996; Marquese, 2008). The history of occupation and economic exploitation through the studied region had quite changed, especially during the peak of the coffee cycle (1830–1890). In 1872, Valença concentrated the largest population of slaves in the region (23,496 people) (IBGE, 2011), which made this municipality stand out as a coffee producer in the national scenario. However, the soil exhaustion and the Golden Law (1888), which abolished slavery, made the region face a coffee crisis (Marquese, 2008). After the coffee crisis, cattle pastures took over the plantations. Currently, even with abundant milk production (Borges et al., 2016), there has been a reduction of pasture areas and an increase of natural regeneration areas (SOS Mata Atlântica and INPE, 2017).

A flowchart illustrates the methodological steps of the research in Fig. 2.

2.2. Forest dynamics

A comparison between 1966 and 2016 evaluated the natural regeneration. First, we digitized the thematic content in topographical map SF-23-Z-A-III-2 (scale 1:50,000) from Brazilian Institute of Geography and Statistics (IBGE) which as produced from aerial photogrammetric survey from 1966. The area covered by this topographical map defined the study area. The photointerpretation in the mask of the study area in the Operational Land Imager (OLI)/Landsat 8 scene (path/row: 217/75, July 25, 2016) generated the data for the most recent landscape

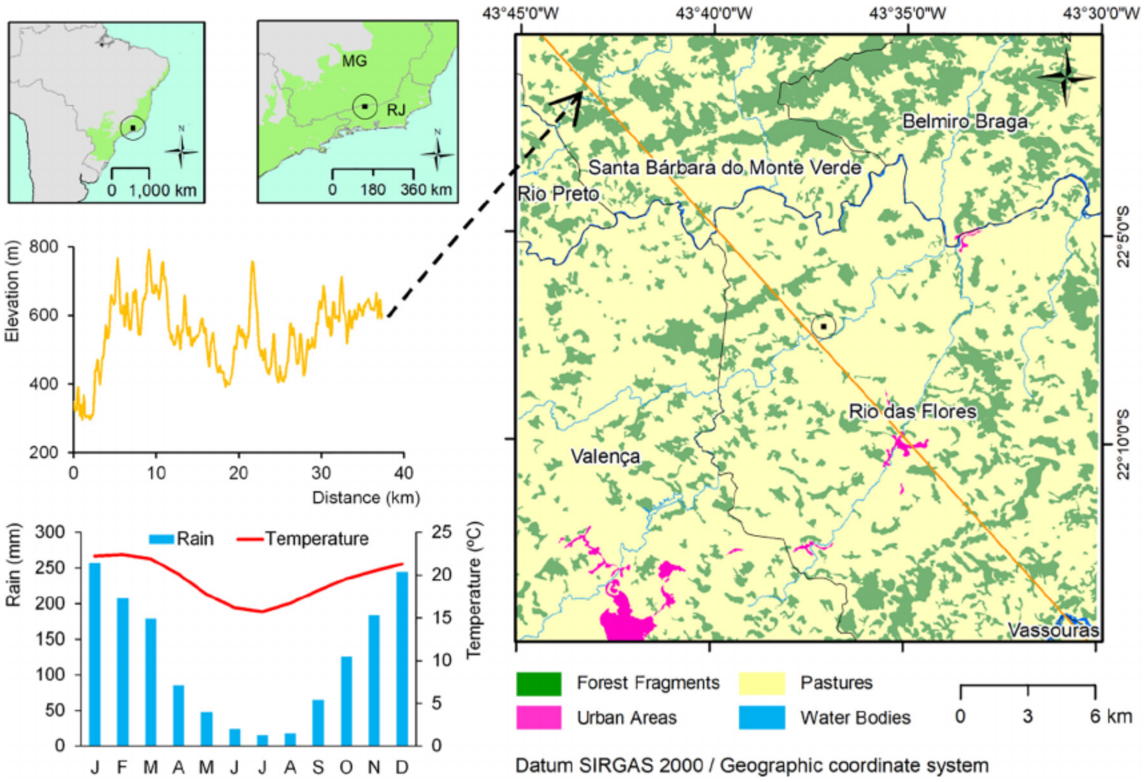


Fig. 1. Study area location between Minas Gerais (MG) and Rio de Janeiro (RJ) Brazilian states, land cover (in 2016), topographic profile (the orange line starts at the lower right) and normal climatological data with average monthly rainfall and temperature observed from 1961 to 1990 (Alvares et al., 2014).

(2016). Still, we interpreted an intermediary landscape collected from Thematic Mapper (TM)/Landsat 5 scene (path/row: 217/75, August 5, 1985). We used the true and false color composites to interpret the Landsat images, i.e., true colors RGB/321 for TM and RGB/432 for OLI and false colors RGB/421 for TM and RGB/532 for OLI. We used the visual interpretation because topographic variation and difference in illumination resulted in low accuracy from hard automatic classifiers.

2.3. Wildfire events

We use a hotspots database (INPE, 2018) to find the wildfires that occurred in the region from 06/01/1988 to 12/31/2016. Hotspots are point-type vector files that correspond to the central position of the pixel of the image sensor in which the characteristic fire temperature has been detected. We use data from all satellites processed by National Institute for Space Research (INPE). These sensors have different characteristics which interfere with the detection of hotspots. The pixel size, for example, varies from 4 km on GOES I-M to 375 m on VIIRS. Currently, AQUA_pm is the reference satellite of the INPE fire monitoring program. NOAA-12 was the reference satellite between June 1st, 1998 and June 31st, 2002. We provide more details about these sensors in the supplementary material. To calculate the hotspots density we used the kernel density interpolator.

The years 2002 and 2014 had the highest rate of hotspots records and were therefore selected to estimate the area reached by fire (fire scars). We chose Landsat images (spatial resolution of 30 m) with low percentage of cloud cover and calculated the normalized burn ratio index (1) to assisted the visual identification of these fire scars (Chuvieco et al., 2002). The Landsat scenes (Supplementary Material 2) contain surface reflectance information (i.e. atmospheric correction) and are available at Earth Explorer of the United States Geological Survey (USGS, http://earthexplorer.usgs.gov). The USGS uses a specific algorithm, described by Masek et al. (2006), to correct the atmospheric effects in the ETM + and OLI scenes.

$$NBR = \frac{NIR - SWIR_2}{NIR + SWIR_2} \quad (1)$$

where: NIR – near infrared (channels ETM$^+$ 4 and OLI 5); SWIR$_2$ – short wave infrared two (channels ETM$^+$ 7, and OLI 7).

2.4. Spatial patterns of natural regeneration, deforestation and fire scars

We used the weights of evidence (WoE) methodology to evaluate how landscape characteristics influenced the spatial patterns of regeneration, deforestation and fire scars. WoE is a Bayesian statistics used to determine the probability of an event given a set of factors of evidence (Bonham-Carter, 1994).

The WoE methodology was initially developed for applications in the diagnosis of diseases and then adapted for the spatialization of favorable areas with minerals, resulting in useful applications for geology (Agterberg et al., 1993). Currently, WoE has been applied efficiently in several environmental studies, such as de Rezende et al. (2015), Soares-Filho et al. (2004), and Teixeira et al. (2009). WoE with positive values indicates a contribution of the environmental variable to the phenomenon under observation, while negative values indicate inhibition. For WoE values close to zero, there is no interference of the variable in the phenomenon.

The Dinamica-EGO software (Environment of Geoprocessing Objects) version 3.0.17 determined the WoE values (Soares-Filho and Rodrigues, 2016). The software is a spatial modeler based on cellular automaton, which, through a transition rule, evaluates the change of state of a cell, considering the state of neighboring cells (Jacob et al., 2008). The transitions considered in this work were deforestation

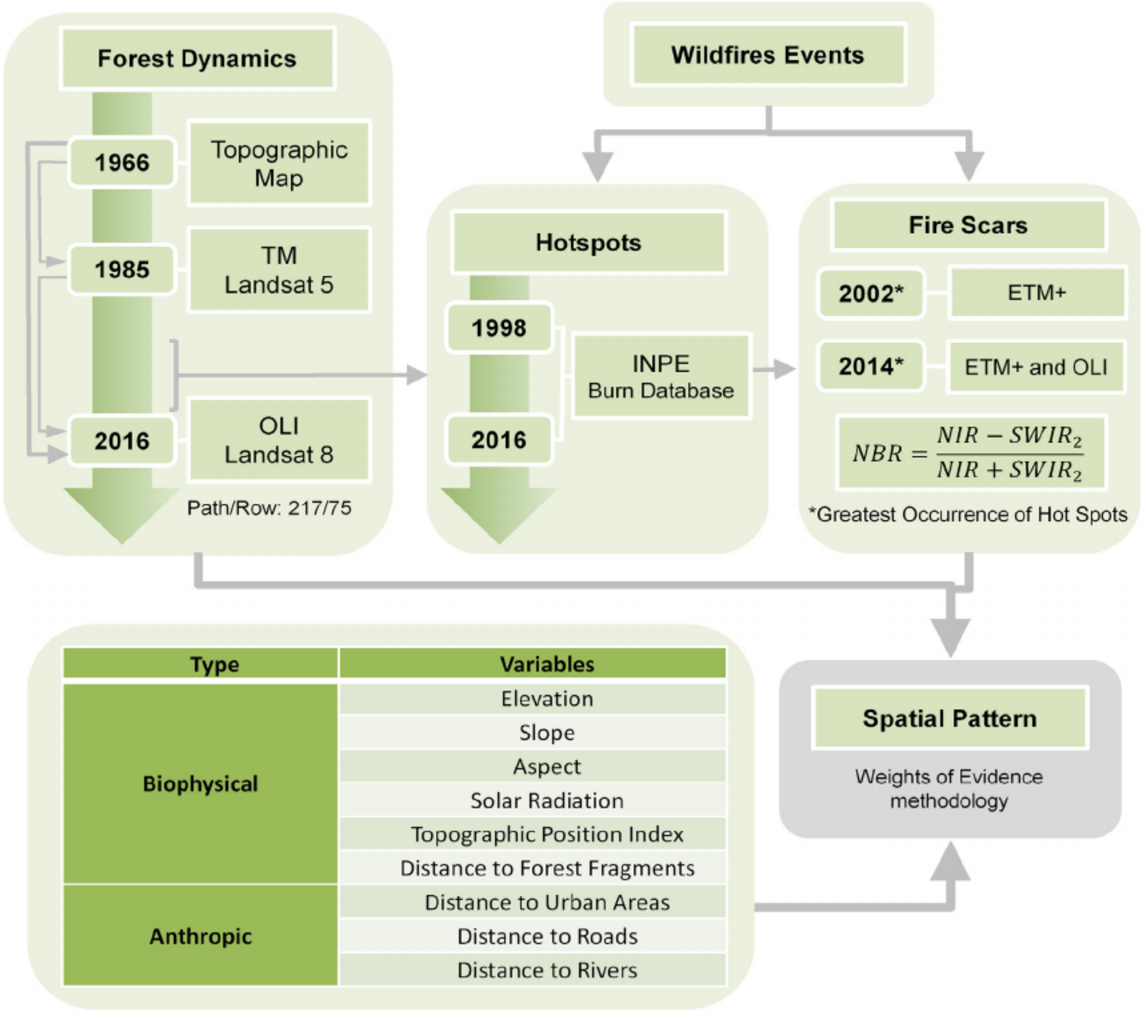


Fig. 2. Workflow.

(forest turned into land for other uses), regeneration (other uses for forest) and wildfires (areas with fire scars).

We consider as natural regeneration the expansion and the appearance of forest fragments. We evaluated the regeneration and deforestation that occurred in the area between the periods of 1966–1985, 1985–2016, and 1996–2016 to calculate the state-transition matrix. We computed the WoE for each period. WoE were also determined for the fire scars identified in the years 2002 and 2014.

The input variables were categorical raster files containing biophysical and anthropic information (Table 1). This data was prepared in ArcGIS 10.5 software.

To calculate the TPI, we used the methodology presented by Weiss (2001), which compares the elevation of each DEM cell to the average elevation of a specific neighborhood. In this study, we considered a neighborhood of 33 × 33 pixels as suggested by Weiss (2001). Positive TPI values represented locations that were higher than the neighborhood average. Negative values represented locations that were lower than their surroundings (valleys). TPI values close to zero represent flat or constant slope areas.

We estimated the global solar radiation using the Solar Analyst algorithm (Fu and Rich, 1999). The Solar Analyst: (1) uses DEM data to evaluate a hemispheric viewshed of each pixel, (2) produces a solar map with the Sun apparent path as a function of the latitude, season, and time of the day. Still, Solar Analyst performs the overlap of the sun map with the viewshed to estimate the direct radiation, (3) calculates the diffuse radiation through a sky map, to determine sectors and the contribution of each of them in function of the zenith and azimuth angles (centroids), (4) estimates global solar radiation through the sum

Table 1
Set of thematic information (raster files in scale 1:50,000 and 30 m spatial resolution) used to identify spatial patterns of natural regeneration, deforestation and fire scars.

Variable	Type	Origin
Elevation (m)	Biophysical	ASTER DEM/USGS
Topographic position index (m)	Biophysical	ASTER DEM/USGS
Slope (%)	Biophysical	ASTER DEM/USGS
Aspect (degress)	Biophysical	ASTER DEM/USGS
Global solar radiation (kWh·m^{-2})	Biophysical	ASTER DEM/USGS
distance to forest fragments (m)[a]	Biophysical	Topographical Map/IBGE and Landsat/USGS
distance to urban areas (m)[1]	Anthropic	Topographical Map/IBGE and Landsat/USGS
distance to highways (m)	Anthropic	Topographical Map/IBGE
Distance to roads (m)	Anthropic	Topographical Map/IBGE
Distance to main rivers (m)	Biophysical	Topographical Map/IBGE
Distance to smaller rivers (m)	Biophysical	Topographical Map/IBGE

ASTER DEM - Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model; USGS - United States Geological Survey (http://earthexplorer.usgs.gov); IBGE - Brazilian Institute of Geography and Statistics (http://loja.ibge.gov.br).

[a] Dynamic variables.

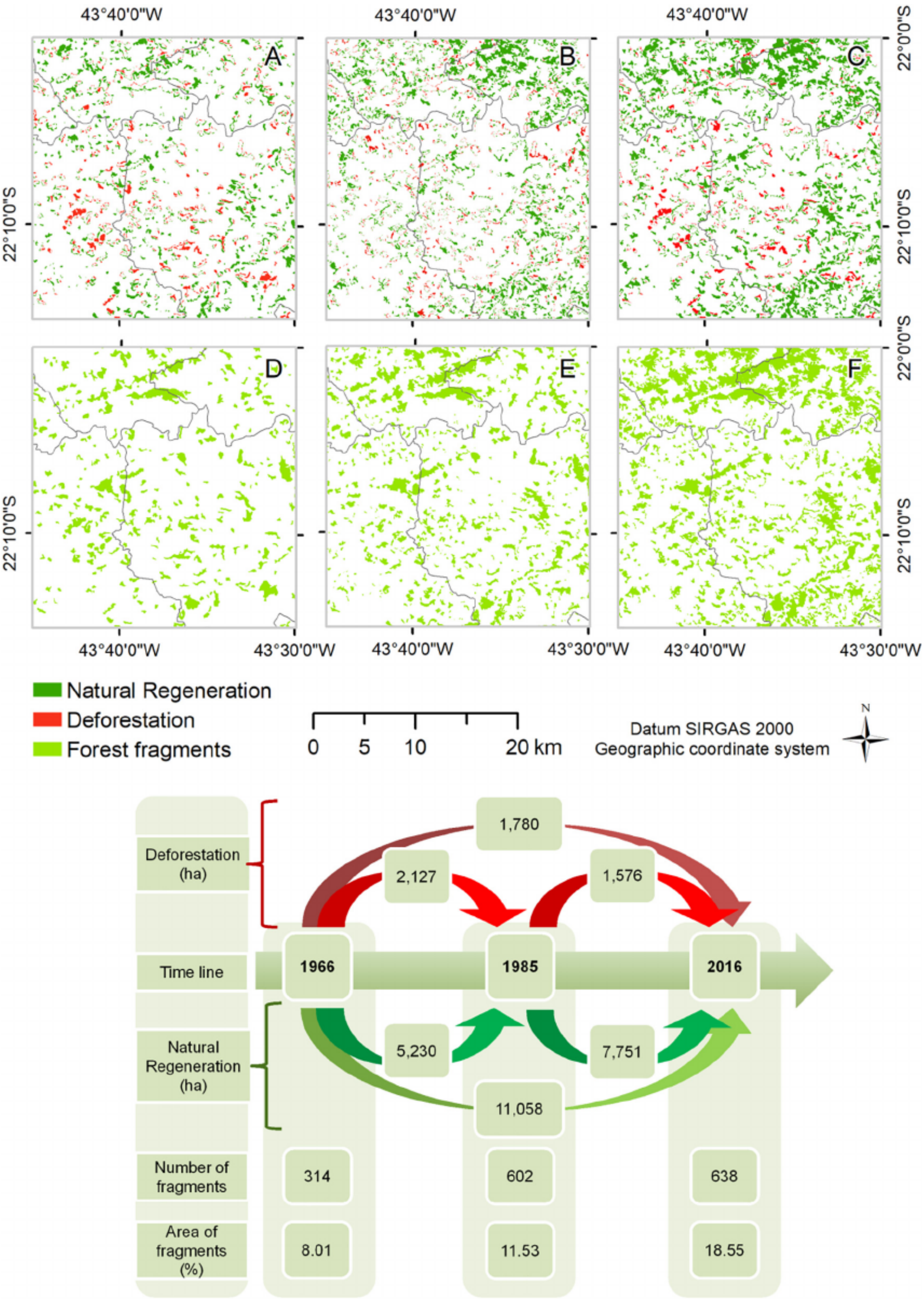


Fig. 3. Forest dynamics between 1966 and 1985 (A); between 1985 and 2016 (B); between 1966 and 2016 (C) and forest cover area in 1966 (D), 1985 (E) and 2016 (F).

of direct radiation and diffuse radiation. As an output, the algorithm offers a matrix file in kilowatt-hours per square meter ($kWh.m^{-2}$). For the time interval, we adopted one year and interpreted the data in $kWh{\cdot}m^{-2}{\cdot}year^{-1}$.

Distance to forest fragments and distance to urban areas are dynamic variables. This means that in Dinamica-EGO these variables are updated in each model iteration (a period of one year). The reference data (1966, 1985 and 2016) were the produced on step 2.2. The distances to highways, roads and rivers were calculated using the Euclidian distance to the thematic content of the IBGE topographical map.

One of the premises of landscape modeling through WoE is that input variables are independent. We also calculated the indexes of association measure CHI^2, Crammers (V), contingency, entropy and joint information uncertainty (U) (presented and discussed by Bonham-Carter, 1994) to analyze the correlation between maps in Dinamica-EGO.

Although there is no consensus for thresholds of exclusion or inclusion of variables, the overall analysis of these statistics features allows a general analysis of the dependence between variables (Soares-Filho et al., 2009). Crammers, contingency, and joint information uncertainty indexes tend to make the analysis less subjective. They vary from 0 (zero), when there is no dependence, to 1 (one), indicating that they are entirely dependent. Bonham-Carter (1994) suggested the adoption of a threshold of 0.5 as an inclusion criterion for Crammer (V) and joint information uncertainty (U).

3. Results

3.1. Natural regeneration and deforestation

Between 1966 and 2016, there was an increase in forest fragments and the area occupied by forest formations. Besides incidents of deforestation, there was a positive outcome of 11,058 ha in the same period (Fig. 3). The loss of forest cover was more intense between 1966 and 1985 (Fig. 3A); however, a deforested area was inferior (2.5 times) than the area under natural regeneration. The natural regeneration process was more intense between 1985 and 2016 (Fig. 3B), surpassing the rate of deforestation in this period by almost five times. The transition matrices indicate a regeneration rate of 0.44% per year and a deforestation rate of 0.65% per year between 1966 and 2016.

3.2. Wildfire events

We found 886 hotspots in the burn database between 01/06/1998 and 12/31/2016 (Fig. 4). The hotspots were more frequent closest to state highways and urban areas in Valença and Rio das Flores (cities in the State of Rio de Janeiro) and to state highways. They reach an average density of 4.5 hotspots per square meter in these regions (Fig. 4).

The year with the highest number of hotspots was 2014 (236) followed by 2002 (110). In 2008, we only observed one occurrence (Fig. 4). The monthly distribution shows a trend in the concentration of outbreaks in August (16.14%), September (30.36%) and October (42.33%) (Fig. 4). This period precedes the rain season (Fig. 1). The AQUA_pm, the reference satellite sensor, represented 32.17% of detections and NOAA-12 registered 10.38%.

In 2002, we identified 306 burned areas from the NBR between May and December (Fig. 5). In that same year, the whole burned area was 5154 ha (15.3% in forest area, 84.3% in pasture, and 0.4% in other coverages), which is equivalent to 5.84% of the study area. In 2014, it was possible to count 4427 ha of burn scars (10.2% in forest area, 89.5% in pastures, and 0.3% in other coverages) between July and November. However, due to the high cloud cover in some images, this burned area may have been underestimated. The polygons of the burned area are between 0.2 and 745 ha, with a predominance of smaller areas.

Predominantly, fire scars are in areas covered by pastures (84.3% in 2002 and 89.5% in 2014). In 2002 and 2014, wildfires respectively affected 16.0% and 14.9%, of the areas that were in regeneration after 1966. Wildifres coincided with 3.0% and 3.1% of deforested areas between 1966 and 2016.

3.3. Understanding forest dynamics and wildfires patterns

Crammers (V) and joint information uncertainty (U) tests indicated independence among all environmental variables used in this study (values below 0.5). Therefore, we used all variables to calculate the WoE. The results of the independence analysis are presented as cross tabulation in the supplementary material.

The WoE indicated the relationships of the analyzed variables with natural regeneration, deforestation and fire scars.

3.3.1. Natural regeneration

We observed that higher altitudes contributed more to the natural regeneration than lower areas (Fig. 6A). Flat or constant slope areas (with TPI close to zero) did not contribute to natural regeneration (Fig. 6B). Nearly flat (0–3%), gentle slope (3–8%) and moderate slope (8–20%) areas inhibited the natural regeneration process. Extreme slope (45–75%) and steep slope (>75%) favored the natural regeneration process (Fig. 6C). Slopes with south, southeast, and southwest orientation have favored regeneration, while north, northwest, and northeast faces have shown negative WoE (Fig. 6D). The smaller the amount of global solar radiation received by the surface, the greater the occurrences of natural regeneration (Fig. 6E). Greater proximity to forest fragments favored regeneration (Fig. 6F). The proximity to urban areas inhibited the process of natural regeneration (Fig. 6G). We observed similar behavior to the distance of the highways (Fig. 6H). Areas close to the roads inhibited the natural regeneration process, and distant areas favored it (Fig. 6I). The areas closest to the rivers (upper or lower order) had negative WoE (Fig. 6J and K).

In terms of orders of magnitude (variation of WoE), the decreasing sequence of the contribution of the variables in the process of natural regeneration were: altitude, global solar radiation; distances to fragments; topographic position index; distance to urban areas; slope, aspect, distance to roads, distance to highways; distance to the main rivers and distances to the smaller rivers, respectively.

3.3.2. Deforestation

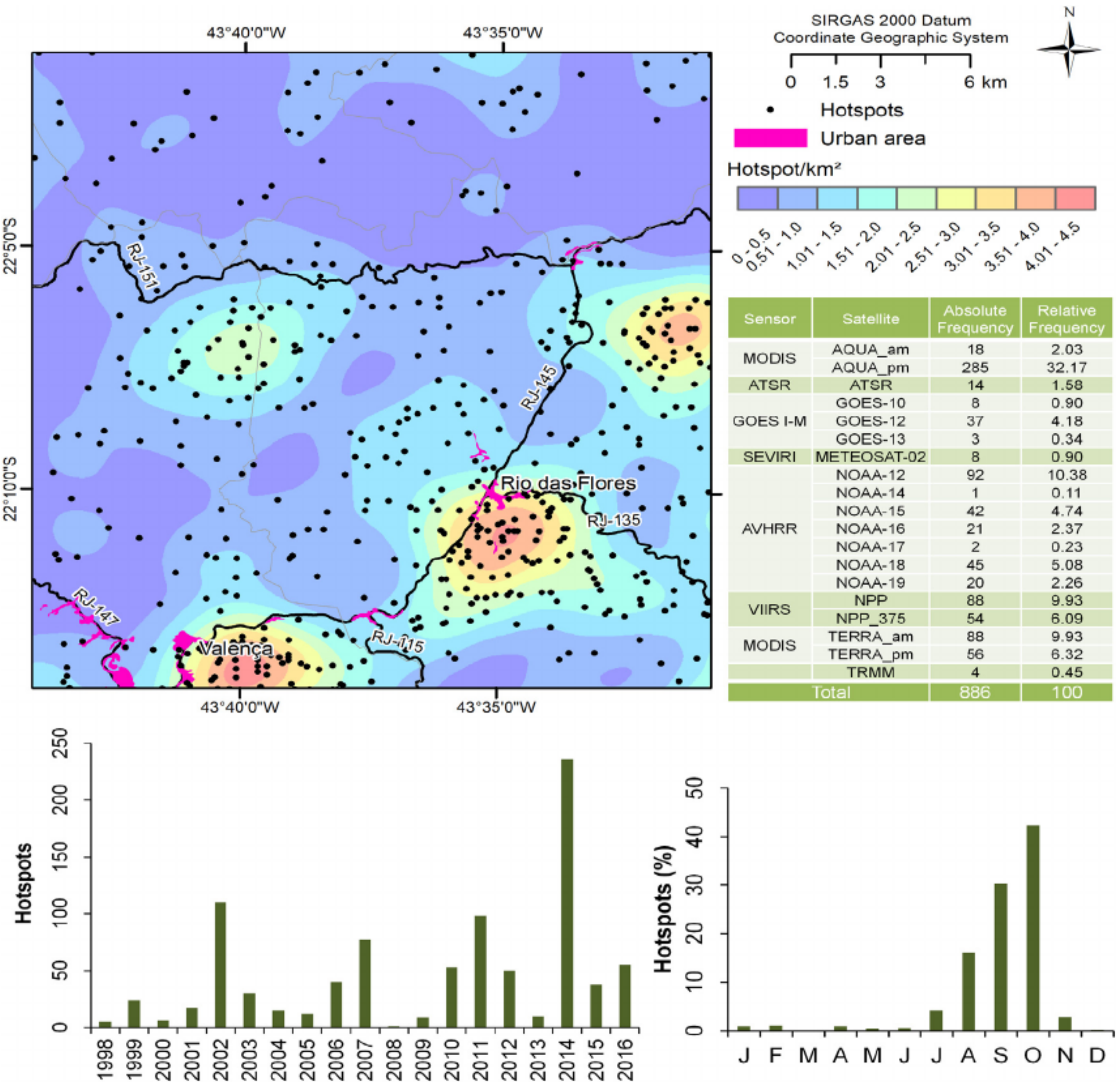
WoE was also used to relate the contribution of variables to deforestation (Fig. 7). We observed that deforestation occurred more frequently at lower altitudes (Fig. 7A) and locations with negative TPI (Fig. 7B). In the slope variable (Fig. 7C), aspect (Fig. 7D), and global solar radiation (Fig. 7E) the behavior was almost the inverse from the natural regeneration process (Fig. 6); The proximity of urban areas (Fig. 7F) and highways (Fig. 7G) favored deforestation. It is possible to observe that deforestation occurred in a slightly more intense way in areas near the rivers (Fig. 7I and J).

3.3.3. Fire scars

In 2002 and 2014, we observed that environmental variables influenced spatial patterns of forest fires and their fire scars (Fig. 8). In 2002, the increase in elevation benefited the presence of burn scars up to 1000 m, and in 2014, up to 700 m. In higher altitudes, the WoE was negative (Fig. 8A). The sites higher than the surrounding area with TPI above zero (Fig. 8B), more inclined (Fig. 8C), with slopes facing north (Fig. 8D), and receiving the most substantial amount of global solar radiation (Fig. 8E) contributed more to the spread of fire, implying larger fire scars in these areas of the landscape. For the other variables, it was not possible to identify a very clear correlation.

4. Discussion

The results of this study demonstrate that the natural regeneration process is active in the region, which represents an opportunity for forest recovery with low economic investment. On the other hand, there are threats to the objective of forest recovery, such as deforestation and the frequent wildfire events. The most recent landscape (Fig. 1) is a mosaic of regenerating vegetation with fragments occurring preferentially in areas more difficult to burn (such as fire refugia).



Sensor	Satellite	Absolute Frequency	Relative Frequency
MODIS	AQUA_am	18	2.03
	AQUA_pm	285	32.17
ATSR	ATSR	14	1.58
GOES I-M	GOES-10	8	0.90
	GOES-12	37	4.18
	GOES-13	3	0.34
SEVIRI	METEOSAT-02	8	0.90
AVHRR	NOAA-12	92	10.38
	NOAA-14	1	0.11
	NOAA-15	42	4.74
	NOAA-16	21	2.37
	NOAA-17	2	0.23
	NOAA-18	45	5.08
	NOAA-19	20	2.26
VIIRS	NPP	88	9.93
	NPP_375	54	6.09
MODIS	TERRA_am	88	9.93
	TERRA_pm	56	6.32
	TRMM	4	0.45
Total		886	100

Fig. 4. Spatial distribution, Kernel density, satellite detection, annual and monthly distribution of hotspots (from June/1998 to Dec/2016).

4.1. *The management of natural regeneration as an opportunity for Atlantic Forest restoration*

The first landscape analyzed in this study, for the year 1966, shows that the area once fully covered by AF had been reduced to 8.01% forest cover. With the declining of the coffee economy and the great world crisis of 1929, livestock farming became an alternative in the region (Borges et al., 2016). From 1966 to 1985, deforestation happened in many areas of forest cover (Fig. 3A), probably to be used as pasture. However, between these 19 years, there were also places where the forest had regenerated.

It was possible to notice the intensification of the regeneration process between 1985 and 2016 (Fig. 3B). In 2016, the study area had 18.55% of forest cover. Even with pasture areas turning to forests, dairy production in this region has intensified (Borges et al., 2016). Recently, dairy farm has lost some of its extensive characters and has become more intensive. Projects like *Embrapa Balde Cheio* (milk production) increased the productive capacity of the lands by adopting more conservationist measures, such as rotational grazing and confinement (Borges et al., 2016). Like Latawiec et al. (2015), this finding demonstrates that sustainable production contributes to forest restoration without conflicts.

de Rezende et al., (2015) also found forest cover increased by 15.3% between 1978 and 2014, at an annual rate of 0.4%, in Trajano de Moraes, also in the state of Rio de Janeiro. They related this process to the decline of rural population observed in that municipality in the same period. The decrease of the rural population relates to the abandonment of many activities in rural areas, which benefits the process of natural regeneration. In the cities of Valença and Rio das Flores, whose predominated the study region, also had a reduction of 49.61% and 59.62% respectively of the rural population between 1960 and 2010 (IBGE, 2011). Besides, the cases raised by Chazdon and Guariguata (2016) demonstrated that natural regeneration is a feasible strategy for large-scale forest restoration in the tropics.

Our analysis focused on quantifying the increase in forest cover without evaluating qualitative parameters. This qualitative characteristic should be studied in future works. In addition to reducing the costs of reforestation, the management of natural regeneration tends to allow the appearance of species that are highly adapted to their environment (Chazdon and Guariguata, 2016; Holl and Aide, 2011). Furthermore, natural regeneration is important for recovering the connection of fragments and retention of water. Better results can be achieved if with species enrichment management (Holl and Aide, 2011; Latawiec et al., 2016).

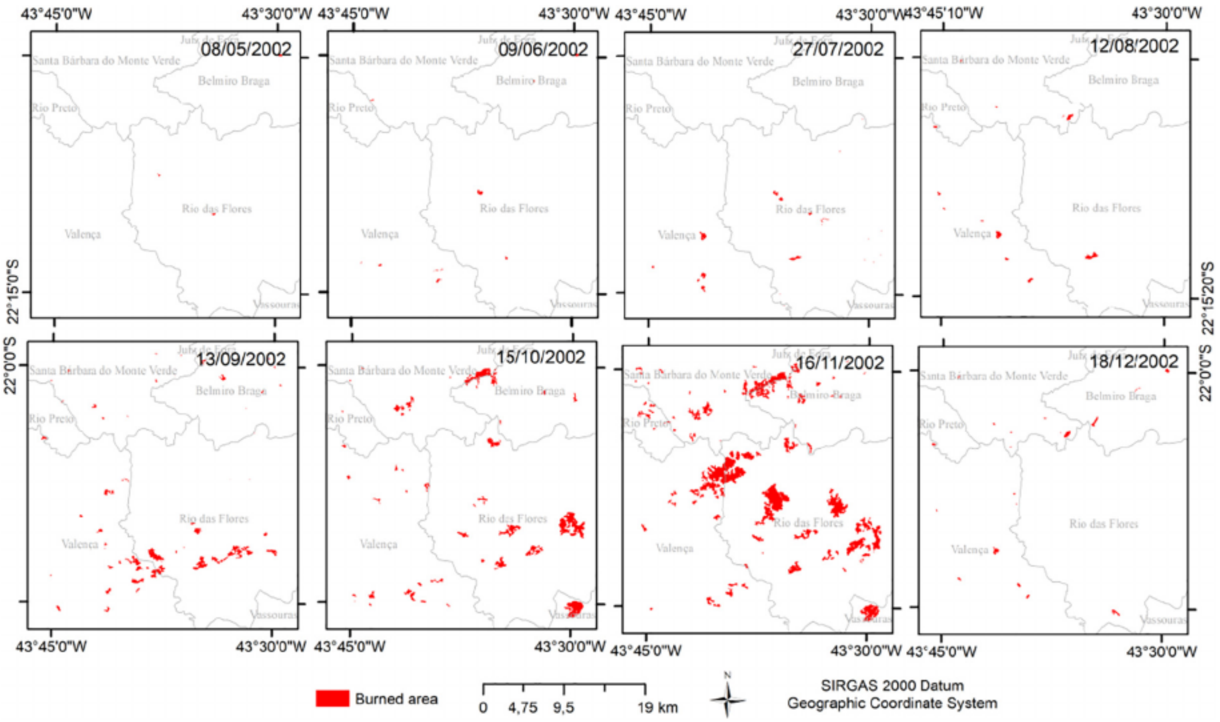


Fig. 5. Fire scars identified throughout 2002 using the Normalized Burn Ratio spectral index in ETM+/Landsat 7 scenes.

4.2. Patterns of natural regeneration and fire scars

The WoE methodology turned possible a qualitative analysis of the relationships between aspects of the landscape, the forest dynamics, and the occurrence of fires. As observed in other studies, biophysical and anthropic variables had related to the spatial pattern of natural regeneration, deforestation (Molin et al., 2017; de Rezende et al., 2015; dos Santos et al., 2016) and forest fires propagation (Carmo et al., 2011; Dickson et al., 2006; Torres et al., 2017).

The proximity to the remaining forest fragments was a key factor for the natural regeneration process, presenting a high weight of evidence in the first 100 m. The closer to the fragments, the higher the number of propagules that reaches the ground, by various forms of dispersion (Bortoleto et al., 2016; Chazdon and Guariguata, 2016).

The areas near the rivers have conditions that contributed to the establishment of plants, such as greater water availability, the presence of animals dispersing seeds, deposition of organic matter, besides being legally protected (Brazilian Forest Code Law 12.651/2012). Thus, it was expected that these areas would favor natural regeneration as observed by (Cabral et al., 2007; Molin et al., 2017; Teixeira et al., 2009). However, we found a reverse behavior (Fig. 6J and K). One explanation for this situation is the concentration of urban areas, highways, and roads in regions close to rivers. Also, when observing the WoE in the process of deforestation, we noticed that there was a trend in higher rates of deforestation in places close to the rivers (Fig. 7I and J).

In addition to high rates of landscape change, including soil sealing, urban matrices disrupt the flow of many dispersers (Bortoleto et al., 2016). The proximity of highways and urban areas is also a factor related to deforestation in other areas of Atlantic Forest (Cabral et al., 2007; Freitas et al., 2010; Teixeira et al., 2009) and other biomes such as the Amazon (Soares-Filho et al., 2004). Future works may clarify, for example, whether the reformulation of the Brazilian Forest Code, since 2012, will decrease deforestation and occupation of APPs. The lower and flat areas also attract greater human occupation, either for housing or for economic activities, which intensifies deforestation in these areas.

In 2002 and 2014, the WoE for burn scars indicated that environmental variables contributed to explaining fire patterns (Fig. 8). Altitude is a variable that generates a gradient in the type of vegetation cover, moisture content, pressure and temperature (Körner, 2007). The relationship between fire spreading and altitude can be positive or negative according to regional characteristics (Dickson et al., 2006; Martínez-Fernández et al., 2013). In this study, both the lower altitudes (below 450 m) and the higher areas (above 750 m) negatively influenced the presence of burn scars (Fig. 8A). In the studied region the typical terrain of *mar de morros* ('sea of hills') dominates and the lower areas coincide with the valleys of the main rivers (Preto River and Paraíba do Sul River) and its tributaries. On the other hand, the higher portions tend to have a slope above 45%, which makes it difficult or even impossible to accommodate housing and agricultural production. These areas are also legally protected (Law 12.651/2012).

Regarding the TPI, we observed that the higher areas concerning the neighborhood favor the occurrence of wildfires (Fig. 8B). These areas are more exposed to wind, sunshine and therefore tend to be less humid than areas in valleys. In southwest Tasmania, the "islands" of rainforest occur preferentially in areas less susceptible to fire events (Wood et al., 2011). As in the region of our study, valleys, depressions, and the southern-facing slopes composed of areas called fire refugia by Wood et al. (2011).

In this research, we have perceived that the slopes which are more exposed to the Sun (north-facing) and steeper facilitate the spreading of the fire (Fig. 8C and D). Others authors reported this behavior (Carmo et al., 2011; Pyne et al., 1996; Torres et al., 2017). The strands most exposed to the Sun receive a higher amount of direct solar radiation, turning the surface warmer and drier. Oliveira et al. (1995) reported differences in the moisture content of forest litter in AF between slopes. In hilly areas, the fire intensity increases because the combustible material is closer to the flames (Carmo et al., 2011).

4.3. Wildfires and their relationships with natural regeneration

Chapter IX of Law 12.651/2012 is exclusively dedicated to the prohibition of the use of fire and the control of wildfires. According to the new

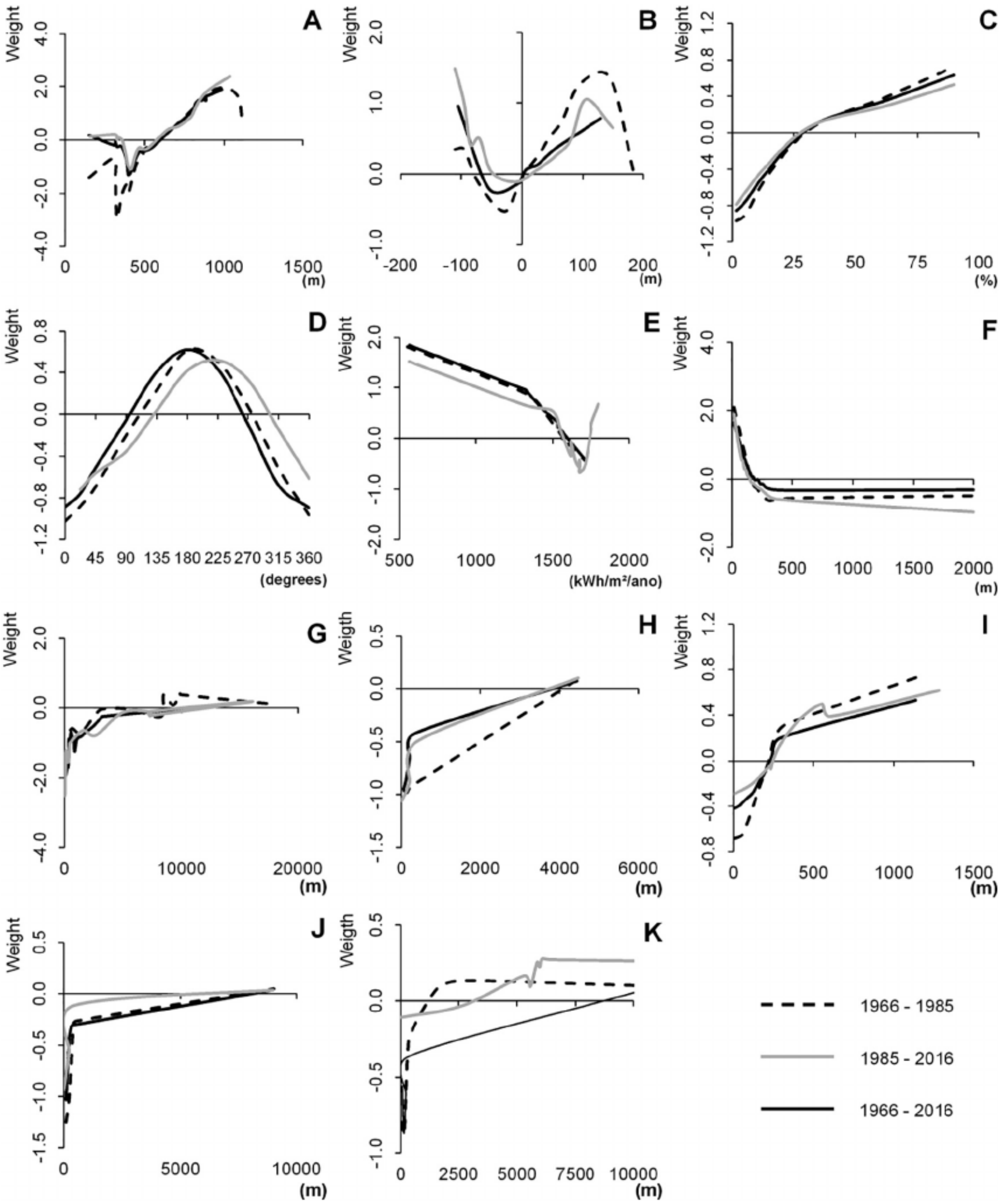


Fig. 6. Weights of Evidence (WoE) of the environmental variables analyzed in the natural regeneration process. A - Elevation; B - Topographic position index; C - Slope; D - Aspect; E - Global solar radiation; F - Distance to forest fragments; G - Distance to urban areas; H - Distance to highways; I - Distance to roads; J - Distance to main rivers; K - Distance to smaller rivers.

law, the use of fire will only be allowed in places or regions whose peculiarities justify the use in agropastoral or forestry practices, after prior approval of the competent state environmental agency of the National Environmental System (SISNAMA). Although controlled burn is an efficient mechanism for forest fire prevention and an inexpensive alternative for area clean-up and pest control (Fernandes and Botelho, 2003), it needs regulation and execution in a safe environment. Otherwise, it can damage forest fragments and regeneration areas.

The detection of hot spots and the predominance of small burn scars are an indication of the frequent use of fire in small farms for the renovation of pastures and agricultural crops (FAO - Food and Agriculture Organization, 2007; Torres et al., 2018). However, once out from control, fire propagates through preferential areas, affecting large areas of land (Fig. 5). The seasonality of vegetation, influenced by the regional climate, is a factor that contributes to the concentration of hot spots in the dry season. During drought, the leaves fall, and it increases the concentration of combustible material with low soil humidity.

The fire, besides the association with high vegetation mortality, also negatively impacts the seed bank and soil structure (Schmerbeck and Fiener, 2015) Even in fire-tolerant biomes, such as Mediterranean ecosystems, the recurrence of fires at increasingly shorter intervals has hampered natural regeneration and reduced species diversity (Tessler et al., 2016). In the AF, Sansevero et al. (2017) evaluated a regenerated forest that was affected by fire 15 years ago. The area showed lower values of species richness, above-ground biomass, and leaf area index in comparison to old-growth forests.

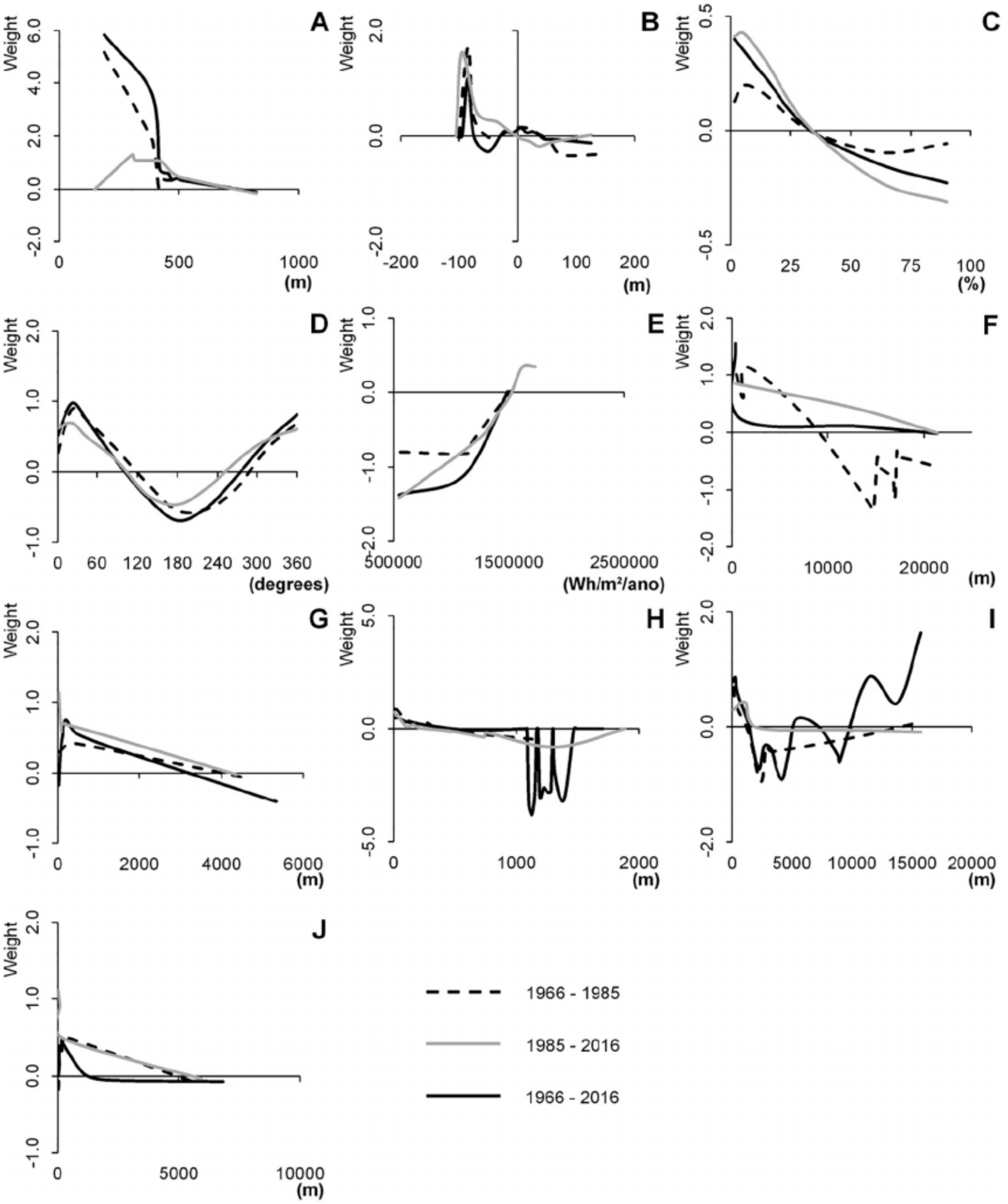


Fig. 7. Weights of evidence of environmental variables in the deforestation process. A - Elevation; B - Topographic position index; C - Slope; D - Aspect; E - Global solar radiation; F - Distribution to urban areas; G - Distance to highways; H - Distance to roads; I - Distance to main rivers; J - Distance to smaller rivers.

The most exciting findings of this study are the analysis of the forest dynamics and wildfires altogether. The patterns of occurrence of forest fires (Fig. 8) are virtually opposite to the natural regeneration patterns (Fig. 6).

The results suggested a relationship between forest dynamics and wildfire in the studied region and contributed to a hypothesis raised by dos Santos et al., (2016), that fire is a modeler of the landscape in the region. The seasonal forest of the region has the potential to regenerate. However, the common wildfires in the area had spread to the farthest areas exposed to Sun and steeper slopes because they are less humid. The recurrence of fires contributes to inhibiting natural regeneration.

These findings have practical applications both at the local level and at lower scales. At the local level, the producer who wishes to adopt natural regeneration as a forest recovery strategy should preferably choose regions close to other fragments and with slopes less exposed to solar radiation. For example, in cases those rural owners have to recompose APP or RL to suit the new forest code. The maintenance of fences and firebreaks is a fundamental step toward the advancement of regeneration. Planting seedlings of fire-tolerant species are a preferable strategy to recover areas most susceptible to wildfires.

For the biome level, this study associated with others contributes to the objective of the Atlantic Forest Restoration Pact (PRMA) to recover 15 million ha by 2050 (Melo et al., 2013). The PRMA was launched on

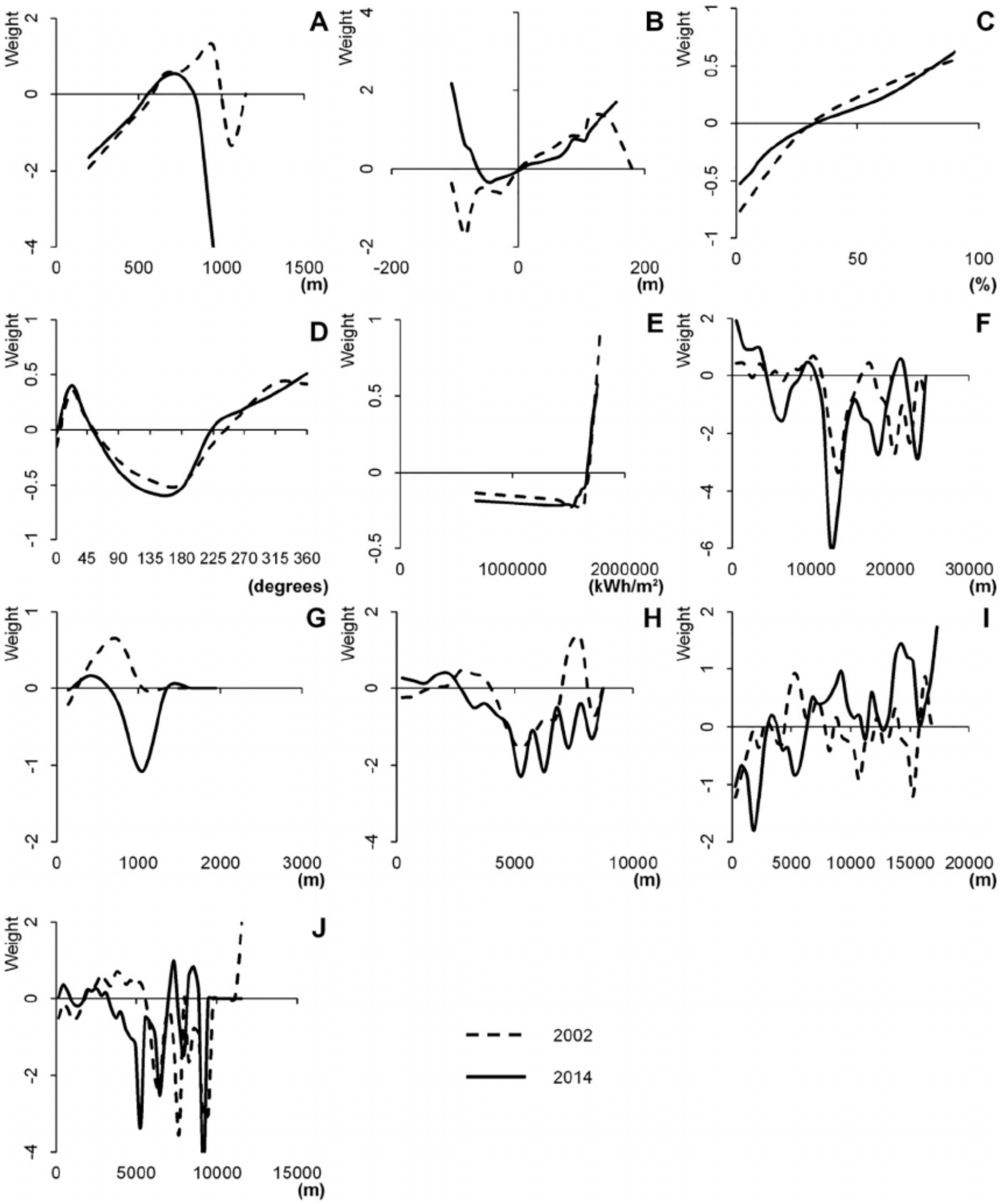


Fig. 8. Weights of evidence of environmental variables in the burned area. A - Elevation; B - Topographic position index; C - Slope; D - Aspect; E - Global solar radiation; F - Distance to urban areas; G - Distance to highways; H - Distance to roads; I - Distance to rivers of higher orders; J - Distance to rivers of smaller orders.

April 7, 2009. As demonstrated in this study, the occurrence of fires in the AF is still common today. We believe that increased surveillance and educational campaigns can reduce the indiscriminate use of fire. The zoning and isolation of strategic areas, based on the observed patterns of occurrence, tend to favor the spontaneous recovery of the Atlantic Forest.

5. Conclusion

The natural regeneration process was responsible for the increase of 11,058 ha of forest cover area between 1966 and 2016, which is equivalent to an average rate of 0.44% per year. This process occurs mainly in areas closer to forest remnants, distant from highways and urban areas, and in portions of terrain that receive the least amount of global solar radiation (valleys and south-facing slopes). Because most of the population is concentrated near watercourses and in the lower areas, these regions are inhibiting the process of natural regeneration. On the other hand, deforestation reduced the area of forest coverage by 1780 ha in 1966, preferentially in areas near urban areas, roads, and highways, and in landscape areas most exposed to solar radiation. Wildfires were frequent, especially in the driest months of the year. The proximity of urban areas and highways favor the occurrence of hot spots and the areas more exposed to the Sun (ridges and steep north-facing slopes) facilitate the spread of fire. In this way, we concluded that fire contributes to inhibiting regeneration in specific areas of the landscape and vegetation develops preferentially in areas of fire refugia.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.09.016.

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