RESEARCH ARTICLE

CONTRIBUTION OF SATELLITE IMAGERY TO THE CHARACTERIZATION OF THE RELATIONSHIP BETWEEN CLIMATE AND PYROLOGICAL VARIABLES OF BUSH FIRES IN THE SAVANNAH ZONE (case of the BOUNKANI REGION)

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ABSTRACT

The present study was undertaken to characterize the bushfire regime and the climatic factors influencing its propagation in the Bounkani region. Thus, this work analyzes the spatio-temporal dynamics of fires and the relationship between climatic variables and pyrological variables. First, it exploits time series of active fires and burned areas from MODIS Active fires (MCD14ML) and MODIS Burned area (MCD60A1) data for the period from 2000 to 2017. The methodology is based on the evaluation of seasonality and fire occurrences, and on the spatio-temporal evolution of fires. The results obtained indicate that, on average, the fire season occurs between the months of November and March, generally corresponding to the dry season. Also, the number of fires and the area burned follow a decreasing trend during the 17 years of study. The months of December and January recorded the highest peaks of burned areas and fire outbreaks respectively. Finally, the analysis of the dependence between climatic variables and pyrological variables by the Pearson correlation method showed the influence of climatic parameters in the outbreak and spread of bushfires in the study area. Precipitation and relative humidity are the best predictors with a negative influence on fire activity, while the positive predictors remain temperature. These variables directly impact fire regime in general. The results of this study will assist policy makers and managers in decision making for the implementation of fire control strategies.

KEYWORDS

Bushfires, MODIS data, Active fires, Area burned, Bounkani Region, Pearson correlation, Climatic and pyrological variables.

1. INTRODUCTION

Bushfires are one of the main direct threats to biodiversity degradation. These fires cause several consequences including devastation and reduction of forest areas, loss of sensitive species, exposure of soils to wind and water erosion, and destruction of wildlife habitats, as well as large areas of agricultural land that are consumed (Scott, 1993; Lewis et al 2006; Laris and Bakkouri, 2008; Kabore, 2010; Agus et al., 2019; Eskandari and Eskandari, 2019; FAO, 1996, 2006, 2009). Notwithstanding these adverse effects, fires are generally practiced for a variety of reasons such as maintaining grazing areas as grassy savannah, cleaning up crop residues, land appropriation and palm wine extractions (Loupe et al., 1995; Fournier et al., 2014; Agus et al., 2019; Christopoulou et al., 2019). Following what has been said above, authors such as reveal that there is a contradictory debate about the impacts of fire on vegetation (Mbow, 2000; Laris and Bakkouri, 2008; Fournier, 2014). This contradiction really proves that our knowledge on the exact effects of fires is still poorly known or appreciated. Under the recurrent threat of bushfires, the technical structures in charge of the issue use multiple fire control and prevention

strategies, the effectiveness of which should be based on in-depth knowledge of the distribution and extent of fires.

In Côte d'Ivoire, studies on bush fires have provided important information, but need to be diversified and completed. These studies focus on the causes and consequences of fires on vegetation, as well as the spatial and temporal evolution of vegetation fires, including the work of (Dje, 2006; SODEFOR 2006; Dosso et al., 2010; Dosso et al., 2011; Dosso, 2012; N'Dri et al., 2011; N'Dri et al., 2012; N'Dri et al., 2013; Soro, 2016; Dje et al., 2017; Kone et al., 2018; N'Dri et al., 2018; N'Dri et al., 2018a, 2018b; Kouassi, 2019). However, the majority of bushfires occur in the central and northern zones, above the "V Baoulé" whose vegetation is dominated by savannahs (pre-forest and Sudanese zones) (Kouassi, 2019). According to some study, it is important to signify that fire risk is primarily related to the characteristics of weather and other ecological conditions of the environment (Sow, 2013; Dowdy, 2020). Although humans are responsible for the majority of fire starts in many parts of the world, climate strongly influences global wildfire activity (Eskandari et al., 2020b; Mbow, 2000). Thus, fire activity develops during the dry season

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when climatic factors favor the flammability of vegetation. Fire frequency and behavior depend on the convergence of fuel conditions, weather conditions, and ignition sources (Roger et al., 2020).

The study of the evolution of bushfires in Côte d'Ivoire using satellite imagery is relatively unknown at the local level because of the lack of knowledge of the advantages of these images, etc. It is currently the most widely used method of monitoring bushfires in the country. It is currently the most widely used method for detecting active fire points and calculating burned areas as well as the degree of environmental disturbance (Barry et al., 2015). Observing information on bushfires over a long enough period of time can provide essential information for the development of prevention and active control policies. It is therefore essential to obtain reliable statistics on the evolution of fires in order to improve knowledge of the phenomenon and to guide the technical and economic choices to be made in terms of prevention and control.

The purpose of our study is to have a real knowledge in the Bounkani region, of the dynamics and the mode of propagation of bushfires in time and space. The use of remote sensing images and Geographic Information Systems (GIS), combined with other conventional thematic data, can inform the determination of the savanna fire regime at the national scale (Jaquin, 2011; Szpakowski et al., 2019). This paper aims to characterize the bushfire regime and climatic factors influencing its spread in order to predict fire behavior in the Bounkani region of northeastern Cote d'Ivoire.

2. PHYSICAL FRAMEWORK OF THE STUDY AREA

It is in the extreme north-east of Côte d'Ivoire, between latitudes 9°56'-8°55' North and longitudes 3°11'-2°38' West, the region covers an area of 22,091 km² (Figure 1). Half of the region is occupied by the Comoe national park. Scheduled in 1926 and founded in 1953 under the name of "Bouna Reserve", the Comoe National Park is listed as World Heritage by Humanity and designated biosphere reserve in 1983, with an area of 1,150,000 ha. The relief is heterogeneous. The rugged parts of the region are to the northwest and southeast. The relief leads to variability in the wind path and it influences the mode of distribution of vegetation according to altitude and fuel load. Geomorphology and relief play an important role in the distribution and frequency of fires (Mbow, 2000). The region benefits from a sub-Saharan climate which includes two seasons (Kambire, 2010). The climate is a main determinant of fires since it characterizes the state and nature of the vegetation as well as the weather conditions. The elements of the climate act directly or indirectly on the fire regime and the nature of the fire events. The vegetation is essentially made up of tree and shrub savannahs with gallery forests. There are forest islands on the plateaus and gallery forests linked to the hydrographic network in the western part of the study area (Guillaumet and Adjanohoun, 1971).

Figure 1: Location map of the study area (SOURCE: Prepared by authors in QGIS v 3.10.13)

3. MATERIALS AND METHODOLOGY

3.1 Fire data

3.1.1 Active fire data

The MODIS (Moderate Resolution Imaging Spectroradiometer) data used in this study are provided by the Terra/Aqua sensor combination, and are adapted for active fire detection (Kaufman et al., 1998; Giglio et al., 2016). Fire detection is based on the contextual algorithm of (Giglio et al., 2016). It is characterized by a long data set built up daily (1 km resolution data). The MODIS active fire data are from the MCD14ML Collection 6 archive used to analyze bushfire dynamics (Giglio et al., 2016). The data are chosen because they address the issue of fire timing without neglecting space.

These products, from MODIS Data Collection 6, contain the attributes on fire points:

- latitude and longitude corresponding to the geographic location of the center point of a 1 km x 1 km pixel;
- the brightness indicating the brightness temperature measured in Kelvin, using MODIS channels 21, 22 and 31;
- the scan and track indicating the spatial resolution of the scanned pixel;
- the radiative power of the fire expressed in Megawatts (MW) corresponding to the intensity of the fire or the radiation power of the fire. It also provides information on the amount of radiant heat measured on the detected fires;
- Detection confidence showing the degree of accuracy or quality of each active fire pixel detected.

In addition to these attributes, the fire point shapefile contains information on the date and time of acquisition of the fire points. These data were produced by the University of Maryland in the United States of America and can be downloaded from the following server: <http://modis-fire.umd.edu>.

3.1.2 Burned areas data

The MODIS burned areas product used is from Collection 6: MCD64A1 of 500m spatial resolution and a daily temporal resolution summarized into monthly burned areas data (Giglio et al., 2015; Giglio et al., 2018). The MODIS MCD64A1 product provides monthly burned surface detection with 500 m accuracy already pre-processed by NASA, available in compressed tif.GZ format (Giglio et al., 2018). This monthly MODIS product MCD64A1 exploits and locates the occurrence of an abrupt change in reflectance at the surface following the method described (Roy et al., 2005). The product defines for each 500m pixel the approximate day of the fire. Our study area is located in window 9 which covers most of West Africa and some North African countries available from April 2000 to now.

3.2 Climatic data

In the framework of this work, the climatic data used come from CHIRPS products (Climate Hazards of Infrared Precipitations and Stations), downloadable on the following link: <ftp://chg-ftpout.geog.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/> and from NOAA National Climatic Data Center products available on line on: <https://data.noaa.gov/dataset/dataset/global-surface-summary-of-the-day-gsod>. These products provide data from 2000 to 2017 in the Bounkani region for the following climatic parameters: precipitation, maximum temperature, minimum temperature and mean temperature (°C), mean relative humidity (%), and wind speed (km/h) from 2000 to 2017. Indeed, these parameters were chosen since they are among the meteorological factors influencing fire behavior (Alvarado, 2012; Oloukoi, 2014). All these data taken at the daily scale are analyzed at daily, decadal, monthly and annual scales.

3.3 Tools

For the preprocessing and processing of the data, we used: a spreadsheet software (Excel) to do the calculations and graphical representations, and a decompressed data processing software (QGIS 3.10); the QGIS is not only a very efficient software for satellite data processing but also a good

database manager. For this work, the data MODIS active fires and burned surfaces were processed using GIS QuantumGIS version 3.10 with a spatial resolution of 500m.

3.4 Implementation of the different methods

3.4.1 Fire image processing

The spatial and temporal analysis of the fires requires the use of the Geographic Information System (GIS). For data processing, the method or technique of extraction and polygonization were used.

3.4.1.1 Active fires

The MCD14ML active fire data from collection 6 was extracted to obtain the fire points following the period from 2000 to 2017. We proceeded to remove the confidence levels of presence of lights ≤ 30 according to (Valea, 2005). Active fire points are ranked on a reliability scale of 1 to 100. Confidence levels are based on the quantitative adjustments of the algorithm in the detection process. It may be useful to exclude false positive fire occurrences (Valea, 2005). Thus, fire points with a reliability greater than 30 were kept for comparison with the studies of to establish a base containing only proven fire points (Caillault et al., 2010). The fire points within the map of the Bounkani region are then clipped. The data thus allows us to highlight the number of fires or number of fire outbreaks for the Bounkani region during the period 2000-2017, as well as the seasonality and occurrence of fires in this region.

3.4.1.2 Area Burned

The monthly MODIS Burned Area Product - collection 6 (MCD64A1) data in Geotiff_win9 format was used to find the area of burned plots. The "Burn Date" layer containing the days of vegetation burn was used. The processing and analysis of Modis MCD64A1 images, referring to the Bounkani region from 2000-2017, bring out the monthly variables concerning the extension of burned areas, and the map of burned areas. We removed irrelevant values. The Modis burn-date data covering a period of one month is presented as a series of elementary images described by several pieces of information (Boschetti et al., 2009):

- 0: unburned;
- 1-366: approximate days of fire corresponding to the Gregorian calendar;
- 900: snow or high aerosol;
- 9998: continental water;
- 9999: marine water (sea and ocean);
- 10000: not classified because not enough data.

The processing only involves pixels with relevant values of "1 to 366" covering the given month that has a higher probability of containing a fire event. Therefore, the other values that describe any other information were removed. The administrative map of the Bounkani region is superimposed on the map layers obtained from MODIS in order to carve out the area of interest. The images were reprojected in WGS84 UTM Z 30N system projection corresponding to the positioning of Côte d'Ivoire on the globe and then converted into a shapefile (vectorization). The calculation of burned areas was performed after polygonization. For this product, the minimum pixel size is 23.4 ha.

3.4.2 Statistical analysis

Within the framework of this study, statistical analyses were carried out in order to evaluate the correlation between the climatic variables and the studied phenomena (number of active fires and burned area). Due to the non-normal distribution of the data of the pyrological variables (see Shapiro test), only non-parametric tests were used for the data analysis. All these analyses were performed in the R 3.4 software available at: <http://cran.r-project.org/>.

3.4.2.1 Correlative statistics (Pearson's r correlation)

The climatic parameters studied in this study are the maximum temperature, the average relative humidity, and the precipitation.

According to several authors such as these parameters would be the basis of the influence of fire behavior (Mbow, 2000; Guiguindibaye et al., 2013; Oloukoi et al., 2014). Furthermore, Pearson correlation was used to show the level of relationship between these climatic parameters and the number of fire detections as well as the area burned. The statistical analysis consists of evaluating the dependence by calculating the Pearson correlation coefficient which measures the linear relationship between the random variables.

$$r = \frac{n\sum XiYi - (\sum Xi)(\sum Yi)}{\sqrt{(\sum Xi^2 - (\sum Xi)^2)(\sum Yi^2 - (\sum Yi)^2)}} \quad (1)$$

Finally, the statistical significance of the value of r will be established by checking whether the correlation coefficient r of the sample deviates significantly from 0.

To do this, we calculate:

$$t = r * \sqrt{\frac{n-2}{1-r^2}} \quad (2)$$

The calculated t is then compared to the tabulated Student's t value with n-2 degrees of freedom. If calculated t is greater than the critical value in the Student's t-table, then it is concluded that there is a significant correlation between the two random variables. Otherwise, the correlation is not significant. The statistical treatment was carried out with the statistical software R 3.4.

The correlation coefficients are in the range -1.00 to +1.00.

- 1.00: a perfect negative correlation
- +1.00: a perfect positive correlation
- 0.00: no correlation or independence between the variables

3.4.2.2 Normality tests (Wilcoxon test)

The non-parametric Wilcoxon test is used to determine whether the data for one variable are significantly different from another. It was applied to compare the means of the number of fires and burned areas studied as well as the climatic parameters. The means were differentiated at the 5% threshold, using the Wilcoxon test.

- If $P < 0.05$: Test significatif (distribution non normale)
- If $P > 0.05$: Test non significatif (distribution normale)

Figure 2: Flowchart of the method used

3.5 Main climatic variables of savannah fires

The climatic data used cover from 2000 to 2017. The parameters used in this study are precipitation, maximum temperature, minimum temperature, and average temperature (°C), average relative humidity (%), and wind speed (km.h⁻¹). These parameters were chosen because they are part of the meteorological factors influencing fire behaviour

(Alvarado, 2012; Oloukoi, 2014). All these data collected on a daily scale are analysed on daily, ten-day, monthly, and annual scales.

3.5.1 Main climatic variable 1: Rainfall

The amount of rain in the region is not uniform. They vary in time and space. According to a study, the area has two seasons which are distributed as follows: a rainy season from April to October with heavy precipitation in July, August, September, and a dry season from November to March (Kambire 2010). January is the driest month. Based on data collected from 2000 to 2017, the average annual precipitation of stations is between 900 and 1,200 mm with an overall average of 1,084 mm per year (Figure 3).

Figure 3: Rainfall average over the region from 2000 to 2017

3.5.2 Main climatic variable 2: Temperature

The evolution of temperatures follows climatic seasonality (Koutsias et al., 2013). There are two major thermal regimes in the region that mark two periods. During the year, the temperature generally varies from 20 °C to 37 °C and is rarely below 19 °C or above 39 °C. A period from June to January, during which the monthly average temperatures are below 30 °C and a period from February to June, during which the average monthly temperatures are around 30 °C (figure 4). The fire season corresponds to the period when temperatures are high.

Figure 4: Minimum, average, and maximum temperatures of the synoptic station 2000-2017

The influence of temperature on fires is linked to its effect on the state of the fuel. This influence can be direct by the heating or cooling of the fuel, or indirect by their influence on parameters such as air humidity. The higher the air temperature, the more intense the fires tend to be (figure 4).

3.5.3 Main climatic variable 3: Relative humidity

The region experiences extreme seasonal variation in the perceived humidity. Relative humidity is between 40% and 50% across the region (Koutsias et al., 2013). Relative humidity affects fuel moisture. Wet fuel is more difficult to ignite. When the relative humidity is low, evaporation becomes more important and dries up the fuel. The occurrence of fires can be conditioned by variations in relative humidity. From the thermal and precipitation data, the ombrothermal curve (figure 5) shows a water excess lasting four to five months depending on the reference stations. Almost all the rains are recorded during this period during which the temperatures are low. This diagram shows the beginning and the end of the wet season.

Figure 5: Ombrothermal diagram of stations in the region

3.5.4 Main climatic variable 4: The wind

Two types of wind blow over the region. These types of wind differ in their origins, their routes and their areological structures (Kouadio, 2015). These winds can be divided into two main groups, the harmattan and the Monsoon. The average hourly wind speed in the region varies seasonally over the year (Figure 6). Average wind speeds vary between 0.6 and 2.3 m.s⁻¹. The highest speeds vary between 15 and 18 m.s⁻¹ and are reached in July when the monsoon flow is maximum. The south-west direction is the dominant direction during the year. In the dry season, the region is subject to the influence of the harmattan. It travels in a north-east direction and dominates the circulation of air masses during the dry season.

Figure 6: Average and maximum wind speed of the synoptic station 2000-2017

4. RESULTS

4.1 Spatio-temporal evolution of fires

4.1.1 Fire seasonality

Fire seasonality was determined from the number of active fires and burned areas detected by the MODIS sensor at monthly intervals over the observation period of 2000 to 2017 (figure 7). Over the past 17 years, 102592 fires were detected and a total of 15694467 ha of vegetative land burned in the Bounkani region. The seasonal distribution of fires in the Bounkani region is presented in Figure 2. It generally indicates that bushfires persist for a large part of the year, with a strong variation in the number of fire points on a monthly basis. In general, the fire season in the Bounkani region runs from November to March. Seasonality is characterized by the start of active fires and burned areas in November, and reaches its peak in December, with fire occurrences of 62618 and, with 11218955.04 ha, the largest area burned over a period of seventeen (17) years. This fire occurrence fades in March and becomes almost non-existent in the following months (April to October). Thus, the fire season lasts 5 months (November to March) in the Bounkani region

Figure 7: Monthly distribution of the number of fires (a) and area burned (b) in the Bounkani region

4.1.2 Number of annual active fire points

The region studied has an area of 2,209,150 ha with 1,109,000 ha occupied by the national park. Figure 6 shows the evolution of the number of annual active fires in the region during the period 2000-2017. The number of fires varies from year to year. The variation is characterized by the alternation of one year at a high abundance of fire with another less abundant. Over the 17-year observation period (2000-2017), 2005 was the year with the highest number of fire points with 8,723 fire points, followed by 2011 with 7,443 fire points and the year 2006 which recorded 7404 fire points while the years 2000, 2001 and 2012 were the years when the least fires were observed: 1 678, 3519 and 4062 fire points, respectively (figure 8).

Figure 8: Annual evolution of active fires from 2000 to 2017

4.1.3 Annual burnt surfaces

The evolution of annual burned areas in the region during the period 2000-2017 is shown in figure 9. The scope of burned areas changes enormously from year to year. We also note that the year 2007, 2015 and 2016 are the years when there were more fires in the region with significant peaks corresponding respectively to 1301928.496, 1 150 280.964 and 1 084 029.091 ha of crossed surfaces by fire which represents respectively approximately 59%, 52% and 49% of the area of the region. The years 2004, 2012 and 2014 are, however, the one that suffered the least damage with 424,340.7627; 441,703.3146 and 559,567.1311 ha crossed by the lights.

Figure 9: Annual evolution of burnt surfaces from 2000 to 2017

4.1.4 Spatial evolution of fires

Monitoring the spatial distribution of active fire points over the 17-year period (2000-2017) indicates that fires are present throughout the entire region. A total of 102,592 fires points was identified throughout the region including Comoe National Park during the period from 2000 to 2017.

MODIS data on burned areas made it possible to map and estimate the areas burned for the period 2000 -2017. The results presented in Table 1 indicate that 15.694 million hectares were burned across the region. This shows the extent of the degradation of plantation vegetation and soil caused by fires in the region. The chronological analysis of active fires shows that during the years of strong socio-political turbulence the number of fires was high, and the sizes of the burnt areas were also high.

Table 1: Summary of results for the fires from 2000 to 2017

Years	Active fires	Burnt surfaces (ha)	Burnt surfaces (%)
2000	1678	682 584.0988	31%
2001	3479	1 039 822.375	47%
2002	6026	958 930.3922	43%
2003	6033	918 988.4866	42%
2004	5769	424 340.7627	19%
2005	8733	862 436.2341	39%
2006	7404	948 484.0762	43%
2007	5672	1 301 928.496	59%
2008	7206	747 218.7418	34%
2009	6502	971 032.693	44%
2010	6050	922 073.3248	42%
2011	7443	865 721.8163	39%
2012	4062	441 703.3146	20%
2013	6930	105 0313.851	48%
2014	4763	559 567.1311	25%
2015	5021	115 0280.964	52%
2016	4513	1 084 029.091	49%
2017	5282	764 950.3219	35%

4.2 Relationship between climatic and pyrological variables

4.2.1 Correlation between numbers of active fires and climatic variables

The results of the analysis of the relationship between active fires and climatic variables are presented in figures 10, 11, and 12:

- The number of active fires is high in the dry season. During the rainy season, there is no fire.
- The number of active fires is high during the period of great heat, at which time the temperatures are at their highest value.
- The number of active fires is high during the period the relative humidity has reached its lowest values.

Figure 10: Interrelation between rainfall and number of active fires

Figure 11: Interrelation between maximum temperature and number of active fires

Figure 12: Average relative humidity interrelation and number of active fires

Table 2 presents the analysis of the correlation between active fires and climatic parameters. The correlation coefficient between the number of fires and the precipitation as well as the relative humidity reveals a negative correlation (-0.6139853) and (-0.6584724) respectively indicating that the numbers of fires decrease with the increase in precipitation and humidity relative as shown in Figure 10 and 12. However, the correlation between the number of fires and the temperature is positive. In fact, the coefficient of 0.348156 indicates that the higher the temperature, the more violent the bush fire becomes (figure 11).

Table 2: Correlation analysis between number of active fires and climatic parameters		
Variables	Correlation coefficient (Pearson)	Significance test (threshold 0.05)
Rainfall	-0.6139853	Not significant
Relative humidity	-0.6584724	Significant
Maximum temperature	0.348156	Not significant

4.2.2 Correlation between burnt areas and climatic variables

Figures 13, 14, 15 show the correlations between the observed climatic parameters and the areas burned from 2000 to 2017. Fires are abundant during the period when precipitation is lowest (figure 13). Burnt areas reach their peaks when temperatures are well above average (figure 14). When the relative humidity reaches its lowest levels, the burnt areas become more and more important (figures 15).

Figure 13: Interrelation between rainfall and burnt surfaces

Figure 14: Interrelation between maximum temperature and burnt surfaces

Figure 15: Interrelation between relative humidity and burnt surfaces

Table 3 shows the correlation coefficient between the burned areas and the precipitation and the relative humidity are inversely correlated by -0.539969 and -0.546899 respectively showing that the burned areas decrease with the increase in the precipitation and the relative humidity. As for the correlation between the burnt areas and the maximum temperature, it is positive of 0.2742469. This observation shows that an increase in temperature increases the radiative power of the lights. Of all these climatic variables correlated with the number of fires and the areas burned, only the relative humidity is significant at the 0.05 threshold. This parameter represents the amount of humidity contained in the air compared to what it could have contained, and it is inversely proportional to the air temperature. From the analysis of figure 12 and 15, it appears that fire is more destructive the lower the relative humidity of the air. Biomass can become wetted when air humidity values are high and make it difficult to start a fire. Relative air humidity plays an important role in the combustibility of biomass.

Table 3: Correlation analysis between burned areas and climatic parameters		
Variables	Correlation coefficient (Pearson)	Significance test (threshold 0.05)
Rainfall	-0.539969	Not significant
Relative humidity	-0.546899	Significant
Maximum temperature	0.2742469	Not significant

5. DISCUSSION

Analysis of the relationships between climatic parameters and numbers of fires as well as burnt areas using Pearson correlation showed that relative humidity, temperature, and precipitation are all predictors of the number of fires and burnt surfaces. These climatic factors strongly influence the ignition capacity of vegetation and the spread of fires. Precipitation and relative humidity are inversely correlated with fire activity, while positive influence predictors remain temperature, all of which directly affect the spread of fire. These results confirm several previous studies assessing the effect of climatic factors on wildfires. A group of researchers identified a negative influence of precipitation on fires (Armenteras et al., 2016). In some study, researchers presented a positive effect of temperatures (maximum, average and minimum) and a negative influence of precipitation on the occurrence of fires and burned surfaces (Koutsias et al., 2013). According to the absence of precipitation combined with the increase in temperature considerably increased the load and the aridity of the fuel (vegetation) in addition, with a lower relative humidity, the fire will start and burn more vigorously due to the low moisture content of the vegetation (Abatzoglou and Williams, 2016).

The fires detected during the study period show that the fire season is generally from November to March in the Bounkani region. This result confirms those published by who showed that fire activity in the savannah zone generally begins from November to April and from November to March in the Zanzan (Dje, 2017). This result is in perfect agreement with those of FIRMS (Fire Information for Resource Management System), which states that there is more fire detected in areas above 8°N latitude than below this latitude. As well as that of who shows in his study that fire activity takes place in the Sudano-Guinean and Guinean savannahs in West

African countries, particularly in Côte d'Ivoire, and this activity is widespread in December (Yao, 2010).

The month of December occupies nearly 90% of the area burned and corresponds to the period of early fires. These results are in agreement with those obtained by Barry et al, 2015 who show that there are more early fires (November, December, January) than late fires (March, April, May) in Guinea. This can be explained by the fact that this period corresponds to the beginning of the dry season and the harmattan, which favor the spread of fires. We note that this period is also chosen by herders to burn savannahs in order to promote grass regrowth before the stress period (Soro et al., 2015). Between 2000 and 2017, our results show a downward trend in the number of fire points, but not in the area burned. Many similar studies in sub-Saharan Africa have shown decreasing trends in the number of fires over the last decades (Giglio et al., 2013).

There are also the results of showed a significant downward trend in the number of fires, fire size and area burned in Africa between 2003 and 2015 using MODIS products. This decrease in fire activity could be the result of consistent climate change mitigation efforts at the national level especially in the region (forestry administration, civil society, etc.). A considerable decrease in the number of fires at the end of these 17 years in our study area may be due to the fact that it rains more in the north of the Ivory Coast than in the south, so the amount of herbaceous biomass produced is considerable and is less flammable. In addition, farmers in the north are very aware of the risks of fire and their impact on their livestock and crops (anarcade) and are more committed to fighting these fires (Govender, 2006).

As well as for the surfaces burned, a very large number of fires was recorded from 2000 to 2010. This peculiarity can be explained by the event that occurred in Côte d'Ivoire during this period, which corresponds to the year of a post-election crisis between 2002 and 2010 that afflicted the administration. The explanations may be due to the result of a slackening in the fire control policy at the local level. Several authors confirm that political events are factors in the spread of fires as a popular expression of discontent (Kull 2002; Tabor et al, 2017). In addition, according to Govender, 2006, this situation can be explained by an increase in demographic pressure leading to a greater number of fires due to poaching and the conversion of savannahs into agricultural land (colonization of savannahs by cashew trees).

In addition, the decrease in burned areas observed in the study area could be explained by the fact that populations set fires early in the dry season. This practice makes it possible to limit the possibility of accidental fires spreading when vegetation desiccation is more pronounced and also to promote the regrowth of vegetation useful for livestock production (Dje, 2017). Also, the return of investors in the financing of conservation activities and the implementation of initiatives such as the REDD+ mechanism (Reduction of Greenhouse Gas Emissions from Deforestation and Forest Degradation) since 2011 could explain this decrease in fire activity. In Madagascar, show a very strong correlation between increased investment in conservation or reforestation and a significant reduction in fires (Tabor et al., 2017).

The Comoé National Park (CNP), which occupies a little more than half of Bounkani (11,090 km²) of our study area, has 10,906,653.63 hectares of forest burned over the study period (2000-2017), representing 69.49% of the burned area. This means that the Comoé National Park is the most affected by fire compared to the other sub-prefectures in the vicinity (National Centers for Environment Information, 2020). These results can be explained by the fact that every year, the CNP experiences periods of so-called early fires (control fires) that are set by park managers and cover 95% of its area (Lauginie, 2007). These results mean that the CNP is subject to more fire risks than other parts of the district; a similar situation as observed and noted by in his study where the Niokolo Koba National Park (KNP), which represents 25% of the images, has more than 30% of the fires identified during an entire season (1996-1997) (Mbow, 2005). The same is true of late fires set intentionally to facilitate hunting by people who trespass in the CNP.

The sub-prefecture of Youndouo is the first sub-prefecture in the department of Bouna to be affected by fire, followed by the sub-prefectures of Ondefidouo and Bouna. Its early vulnerability to fire is explained in part by the distribution of vegetation landscapes that are largely grassy savannah dominated by a herbaceous layer (MODIS, 2020). It can also be explained by the movement of the ITD towards the south, which exposes the department to the Harmattan from November onwards, causing a water deficit that is favourable to the outbreak of fires. This can also be explained by the fact that people start fires early in the dry season in order to limit the possibility of accidental fires spreading when the vegetation dries out more, and also to encourage the regrowth of vegetation useful for livestock farming.

In general, the department of Bouna is more affected by fire than the other three departments. This department is defined as a cultivated area located in the southeast of the CNP and has experienced more fire occurrences than those located in the southwest and north, as these populations practice brush fires (slash and burn agriculture) especially during the month of November. Bush fires are particularly common in areas of high agricultural production. They are often the result of cultivation practices, hunting activities, palm wine extraction, or beverage distillation.

Compared to the departments of Bouna, the department of Nassian and Doropo does not seem to be very conducive to the outbreak of fires. Indeed, despite many characteristics, particularly climatic, that are normally favorable to the passage of regular fires in this department. This may be due to the vegetation of these localities, which seems to be resistant to fires because it is made up of dense forest and gallery forest with few pyrophytes. The decrease in burned areas during the period 2000-2017 can be explained on the one hand by the decrease in rainfall and on the other hand by the presence in the field of a water and forestry brigade that participates in equipping farmers with firefighting equipment and has strengthened awareness sessions.

6. CONCLUSION

The analysis of the impact of climatic parameters on fire activities showed the influence of climatic parameters on the propagation of bushfires in the study area. Thus, the hotter and drier the weather, the drier the vegetation and the higher the fire risk. Precipitation and relative humidity are the best predictors with a negative influence on fire activity, while temperature remains the best predictor. These variables directly impact the fire regime generally. The study of the characterization of the bushfire regime showed that the temporal analysis of the images leads to a seasonal character of the fires. The fire season in the region is circumscribed from November to March. The most affected areas are located in the Bouna department. These differences are explained by vegetation types and climate variations. The months of December and January recorded the highest values of burned areas and fire outbreaks respectively. Annually, the year 2005 recorded the highest number of fires, while the year 2007 had the largest areas destroyed by fire. The distribution and magnitude of fires are not the same throughout the region.

The advantage of using MODIS data lies in their high temporal resolution, although their spatial resolution is subject to limitations that overestimate or underestimate the extent of burned areas in places where large areas are not of interest. Regarding the physical characteristics of the images, it should be noted that the size of a pixel (spatial resolution) is 500m, some burned surfaces whose size is much smaller than the pixel are invisible to the sensor. For this purpose, Images with better spatial resolution (LANDSAT with a spatial resolution of up to 15m for example) should allow for much more detailed and accurate estimates. Their disadvantage is their temporal resolution (16 days) but will allow to validate the results given by MODIS. These results also open up the possibility of using fire simulation models to predict actual fire behavior for future and past events to better understand the long-term effects and spread of bushfires on ecosystems, biodiversity and environmental pollution.

CONFLICT OF INTEREST

The authors declare that there is no potential conflict of interest regarding the publication of this work.

AUTHOR CONTRIBUTIONS

K. Sie was responsible for searching the bibliography, selecting the relevant references, revising the final version of manuscript, writing and original draft preparation. T. J. H. Coulibaly, was responsible for conceptualization, supervision, revising the final version of manuscript, reviewing and editing. N. Coulibaly, I. Savane, L. D. Gone, K. C. A. Kouadio, H. S. J. P. Coulibaly, S. Cissé, I. Camara, G. Sylla, was responsible for conceptualization, supervision, investigation and reviewing.

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