Identified main fire hotspots and seasons in Côte d'Ivoire (West Africa) using MODIS fire data

AUTHORS:
Tionhonkélé D. Soro[1]
Moussa Koné[1]
Aya B. N'Dri[1]
Evelyne T. N'Datchoh[2]

AFFILIATIONS:
[1]Laboratory of Ecology and Sustainable Development, Faculty of Natural Sciences, Nangui Abrogoua University, Abidjan, Côte d'Ivoire
[2]Atmospheric Physics Laboratory, Faculty of Structure of Matter and Technology Sciences, Félix Houphouët Boigny University of Cocody, Abidjan, Côte d'Ivoire

CORRESPONDENCE TO:
Tionhonkélé Soro

EMAIL:
soro.drissa1@univ-na.ci

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Biomass burning has become more frequent and widespread worldwide, with a significant proportion occurring in tropical Africa. Fire dynamics have been generally studied at global or regional scales. At local scale, however, fire impacts can be severe or catastrophic, suggesting local analyses are warranted. This study aimed to characterise the spatio-temporal variations of vegetation fires and identify the main fire hotspots in Côte d'Ivoire, a country of West Africa, one of the world's burn centres. Using MODIS-derived fire data over a 10-year period (2007–2016), the number of fire days, active fires and fire density were assessed across the entire country. In the southern part dominated by forests, fire activity was low. Three main fire hotspots were identified between 2°30'–8°30'W and 7°00'–10°30'N in the North-West, North-East and Central areas all dominated by savannas. In these areas, Bafing, Bounkani and Hambol regions recorded the highest fire activity where fire density was 0.4±0.02, 0.28±0.02 and 0.18±0.01 fires/km²/year, respectively. At national scale, the annual fire period stretched from October to April with 91% of fires occurring between December and February, with a peak in January. Over the decade, there was a decreasing trend of fire activity. Fire density also was negatively correlated with rainfall >1000 mm for the synchronic analysis, whereas fire density was positively correlated with rainfall in the previous years. Results suggest that the positive relationship between the previous year's rainfall and fire activity could operate on a cycle from 1 to 4 years.

Significance:

- Three fire hotspots were found primarily in savanna vegetation, which burns more regularly than forest-dominated vegetation.
- The fire season occurs over 7 months, the majority of active fires (91%) occurring in just 3 months (December-January-February) with a peak in January (39%).
- Fire activity has declined over the past decade with a return time of above-average fires from 1 to 4 years.
- Fire density is positively correlated to the amount of rainfall in preceding years, whereas fire density and rainfall of the same year were negatively correlated in the region of rainfall >1000 mm.

Introduction

Fire is considered to be a major determinant of the distribution and function of the world's savanna types.[1] Fire has played a significant role in shaping these landscapes, particularly in Africa. Indeed, the African continent has been known as 'the fire continent' due to the high number of fire occurrences[2], favoured by precipitation irregularities. These irregularities lead to the alternation of wet and dry seasons, with dry seasons favouring fires.

The ability of humans to manage fires is still imperfect and may become more difficult in the future with climate change and growing human populations which tend to increase the risk of fire ignitions.[3] Although fires have provided several environmental services over millennia, they can also impact negatively on the environment and socio-economic activities, especially in recent decades. For example, the burning of areas that have been deforested due to human actions[4] contributes to increasing greenhouse gases, aerosols and other gases such as carbon monoxide and ozone emission into the atmosphere[5,6]. Thus, vegetation fires have a direct impact on climate change and air pollution. Moreover, frequent fires can cause soil erosion and reduce soil fertility.[7] Most fires that have occurred in tropical ecosystems in the recent decades have impacted human health and have caused billions of dollars of damage to economies[8,9], especially during the dry season in rural areas where fire remains very difficult to control. In addition, uncontrolled fires are frequent in tropical regions and elsewhere, with those of the tropics being less studied.[10] This is the case for West African countries with high fire activity such as Côte d'Ivoire.[11]

Fires in African savannas are modulated by climate that determines burning timing and fire onset. Thereby, global climate change will increase both the risk of extreme fire events[12] and fire frequency[13]. Predicting where and when extreme fire events will occur remains difficult.[14] It is therefore necessary to better understand fire dynamics for future disaster prevention which may allow mitigating fire socio-economic damage. Fire dynamics are more often investigated on global and regional scales. Even if small effects of fires are reported at global scale, their impacts at regional and local scales can be, respectively, severe and catastrophic.[10] In Côte d'Ivoire, fire damage is recurrent and occurs each year in more than half the country. A large percentage of the Ivorian population lives in a fire-prone rural area.[15] Thus, local analysis of temporal and spatial variations of fires in Côte d'Ivoire is necessary in order to identify the fire-prone areas and to better understand fire dynamics, both recent and potential future dynamics. This will provide very useful information for fire users and decision-makers.

To address this subject, the Moderate Resolution Imaging Spectroradiometer (MODIS) data are often used due to the fact that the sensor was specifically designed and developed to detect active fires.[16,17] Several studies have been performed in a range of countries and regions, from meso-scale to local scales with high resolution to investigate the human role and other drivers underlying fire variability.[18,19] For Côte d'Ivoire, some fire studies have focused only on protected areas[20,21], excluding rural areas that are more fire prone. Others have been carried out over several countries[11,22], making it impossible to establish fire dynamics and focus on risk areas at the national level.

The aim of this study was to characterise the spatio-temporal variations of fires and identify the main fire hotspots in Côte d'Ivoire. The study also addressed the following questions:

1. Where are the main fire hotspots in Côte d'Ivoire located?
2. Do the periods of fire occurrence and of fire peaks vary among regions?
3. What are the changes in fire variables over the recent decade?
4. What are the drivers of fire density (fires per unit area)?

Methods

Study area

Location and climate

The study area covered the entire territory of Côte d'Ivoire which extends over 322 462 km^2, located in West Africa between 2°30'–8°30'W and 4°30'–10°30'N (Figure 1). The human population density of the country averages about 80 inhabitants/km^2, varying from one region to another as shown in Table 1.[15] The climate is controlled by the north-south migration of the Inter-Tropical Convergence Zone (ITCZ), similar to the wider West African region. This produces an alternation of wet and dry seasons within each year. Biomass burning patterns also follow the seasonal shift determined by the ITCZ.[23]

Two main climate types can be distinguished:

1. The humid equatorial climate, covering forest areas in the South, is characterised by four seasons with mean temperature of about 28 °C. Two rainy seasons occur: a long one from April to July and a short one from September to November. Two dry seasons also occur: a short one in August and a long one from December to March.
2. The tropical climate in the Central and North is generally characterised by a single rainy season from June to September and a long dry season from October to May. Generally, temperatures vary between 14 °C (mean minimum, in December–January) and 36 °C (mean maximum, in March).

Overall, there is a strongly decreasing precipitation gradient from South to North across the country. The mean annual rainfall varies from 1600 mm/year to 1800 mm/year in the South, in the ombrophilous area; then moving northward, from 1300 mm/year to 1500 mm/year in the semi-deciduous area, from 1100 mm/year to 1300 mm/year in the forest-savanna area, from 800 mm/year to 1000 mm/year in the sub-sudanian area, and from 500 mm/year to 800 mm/year in the northernmost Sudanian area. This south-north precipitation gradient is associated with changes in the dominant vegetation type as described below.

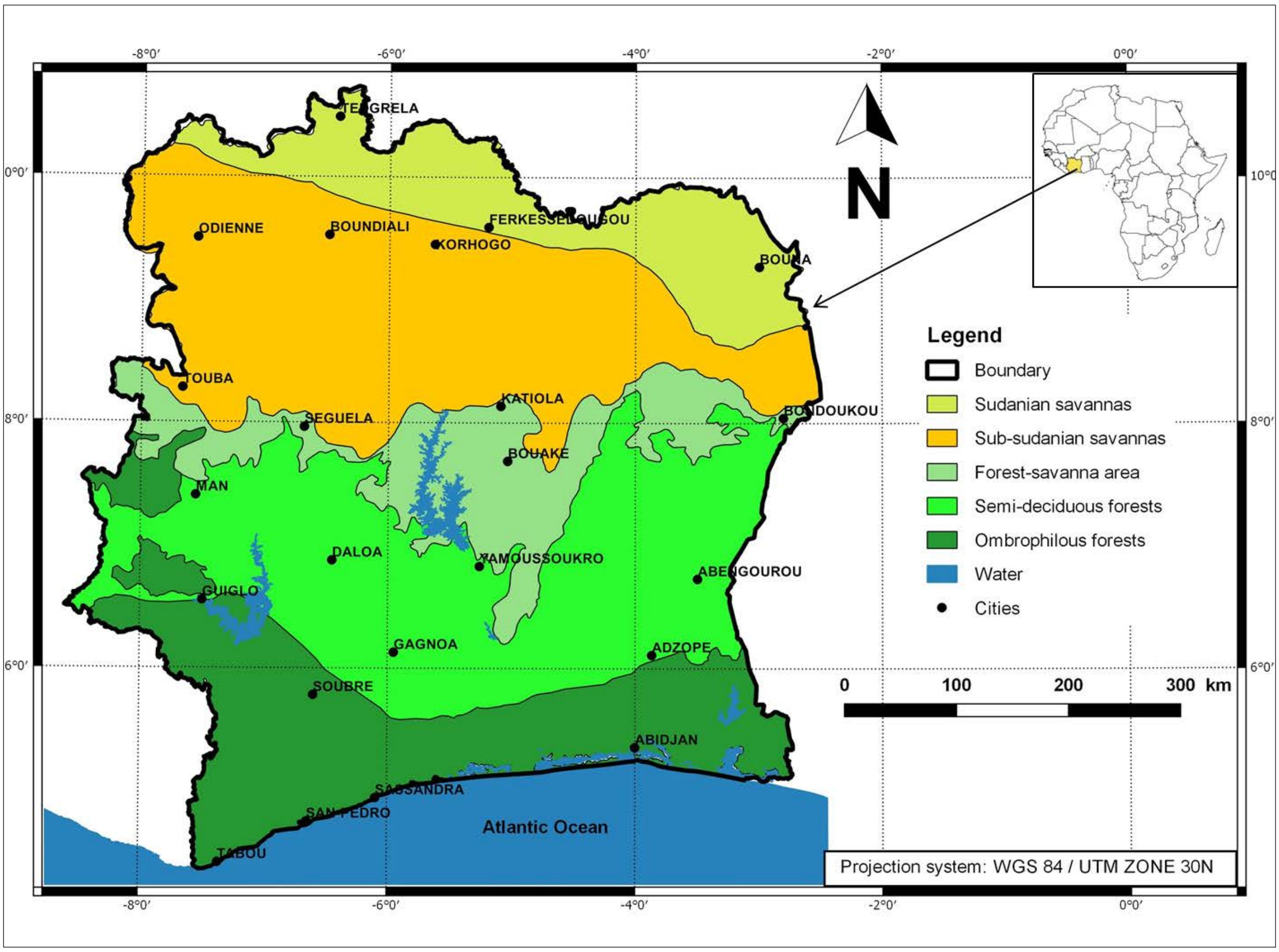

Figure 1: Study area defining the main vegetation types.

Table 1: Human population densities by region of Côte d'Ivoire.[15]

Region	Ecoregion	Vegetation type	Density (inhabitants/km²)
Abidian District	Guinean	Ombrophilous forest	2221.52
Agnéby-Tiassa	Guinean	Ombrophilous forest	66.83
Belier	Guinean	Forest-savanna	50.93
Cavally	Guinean	Ombrophilous forest	40.73
Gbôklé	Guinean	Ombrophilous forest	55.47
Gôh	Guinean	Semi-deciduous forest	119.57
Grands ponts	Guinean	Ombrophilous forest	54.43
Guemon	Guinean	Semi-deciduous forest	118.63
Haut-Sassandra	Guinean	Forest-savanna	80.57
Iffou	Guinean	Semi-deciduous forest	34.86
Indénié-Djuablin	Guinean	Semi-deciduous forest	80.99
Lôh-Djiboua	Guinean	Ombrophilous/semi-deciduous forest	82.95
Marahoué	Guinean	Forest-savanna	99.23
Mé	Guinean	Ombrophilous/semi-deciduous forest	62.49
Nawa	Guinean	Ombrophilous forest	114.55
N'Zi	Guinean	Semi-deciduous forest	66.55
Moronou	Guinean	Semi-deciduous forest	52.87
San-Pedro	Guinean	Ombrophilous forest	64.63
Sud-Comoé	Guinean	Ombrophilous forest	84.26
Tonpki	Guinean	Ombrophilous/semi-deciduous forest	80.80
Yamoussoukro District	Guinean	Semi-deciduous forest	101.59
Bafing	Guinean/Sudanian	Forest-savanna/Sudanian savanna	21.16
Béré	Guinean/Sudanian	Forest-savanna	29.32
Gbêkê	Guinean/Sudanian	Forest-savanna	110.64
Worodougou	Guinean/Sudanian	Forest-savanna	24.50
Gontougo	Guinean/Sudanian	Sub-sudanian savanna	39.78
Hambol	Guinean/Sudanian	Sub-sudanian savanna	22.49
Bagoue	Sudanian	Sub-/Sudanian savanna	35.22
Bounkani	Sudanian	Sudanian savanna	12.09
Folon	Sudanian	Sudanian savanna	13.32
Kabadougou	Sudanian	Sub-/Sudanian savanna	13.81
Poro	Sudanian	Sub-/Sudanian savanna	57.00
Tchologo	Sudanian	Sudanian savanna	26.40

Vegetation and structure

The dominant vegetation types, as delineated by Guillaumet and Adjanohoun[24], are shown in Figure 1. Ombrophilous forests in the south of the country consist of different types of evergreen forests. The canopies are the tallest, with some trees up to 40 m tall, and with total canopy cover of 100% in some places. The herbaceous stratum is diffuse. Semi-deciduous forests are humid forests with a structure comparable to ombrophilous forests, but with a sparser canopy cover. The herbaceous stratum varies from 1 m to 2 m tall. In the forest-savanna area, the landscape has a combination (a patchwork) of dry forest and humid savanna. Gallery forest and island forest are frequent. *Borassus aethiopum* savanna is the most common shrubland savanna. The coverage of the shrubby and woody strata can reach 50% and 35%, respectively. The herbaceous stratum is nearly continuous, with up to 90% coverage over some places, providing fuel favourable to fires. Sub-Sudanian and Sudanian areas are located in the north over the eighth parallel. Although the Sudanian area is the driest part of the country, these two areas have similar vegetation characteristics, mostly dry savannas. Some gallery and island forests are also present with a taller woody stratum. The important herbaceous stratum (dominated by Andropogoneae grasses) and the long dry season lead to frequent fires here.

MODIS fire data source

One of the sensors in the Earth Observation System, MODIS is a multi-temporal remote sensing device. The active fire data used in this study are derived from MODIS imagery and provided by the Fire Information for Resource Management System (FIRMS) of the US National Aeronautics and Space Administration (NASA) and the University of Maryland (USA). The MODIS instrument is equipped with Terra and Aqua satellites providing observations of Earth's surface four times per day: at 10:30 and 22:30 local time for Terra and at 13:30 and 01:30 for Aqua (times are for the Côte d'Ivoire). Thus, fire pixels are recorded four times per day, during the time of the satellite's overpass.

We used MODIS observations ranging over 10 years, from the start of the 2006/2007 fire season to the end of the 2015/2016 fire season. Thus, data were acquired according to fire seasons. Hereafter, each fire season is indicated using only the final year (as fire seasons span two calendar years). For example, the 2006/2007 season will be referred to as the 2007 fire year. The data cover all 31 regions and two autonomous districts of Côte d'Ivoire, i.e. the whole territory.

The original data were daily fire products with full spatial resolutions of 1 km (until 2010), 500 m (between 2010 and 2015) and 375 m (in 2016). Because these fire products were unmanageably large to be used in their entirety, they were plotted into fixed grids of 0.5°x0.5° in size in which fire counts were made.[25] Using the algorithm developed by Giglio et al.[16], MODIS data are processed using the Rapid Response System. The processed data are made available through the Joint Research Centre (JRC) web server (http://firetool.jrc.ec.europa.eu/) of NASA's FIRMS. Monthly maps of fire occurrence are available for download in shapefile (.shp) format and can be used in a GIS environment.

Data processing

Fire data acquired were imported in QGIS software in which fire pixels were overlaid with the shapefile of Ivorian administrative boundaries. Water bodies were masked out to avoid false alarms and ensure the accuracy of detected fire hotspots, as suggested by Giglio[25]. Once processed in QGIS, attribute tables of fire data were exported for descriptive statistical analysis. The spatio-temporal distribution of fire was investigated, based on the number of fire days, the number of active fires and fire density.

For all parameters (number of fire days, number of active fires and fire density), any value that was higher than the national average was designated by 'above-average' and a lower value by 'below-average'. Regions with above-average fires were considered as high-risk areas or fire-prone areas (relative to averages). Fire activity was tested for significance using Pearson's correlation coefficient test in R software.[26]

Active fires and number of fire days

An active fire is any fire detected by the satellite when it is still burning. Whenever a pixel was recorded with an active fire, that designation of a fire occurrence (or a fire pixel) was counted just one time during the relevant fire season. Active fires were recorded per region for each year (each fire season). Next, the spatial variability of the fire occurrences was mapped by administrative subdivisions of Côte d'Ivoire (i.e. 31 regions and two autonomous districts). Temporal variability was calculated by years and on a monthly basis. The map of active fires was produced using only fire pixels with a confidence level of 100% (high confidence), in order to better focus on fire hotspots (Figure 2).

A fire day was defined as a day on which at least one active fire (i.e. fire pixel) was detected by the MODIS satellite. Thus, the total number of fire days, defined as the sum of the fire days, was determined by year and by administrative subdivision.

Fire density and fire-prone regions

Fire density is defined as the number of fire pixels per 1000 ha detected over a given period of time.[20] It was analysed spatially and temporally, and is presented here as fires/km²/year. Based on the numerical size of fire density, fire-prone regions were identified. A 'fire-prone' region is defined as a region with above-average fires over the study period. For more accuracy on fire dynamics over main fire hotspots, the fire density of the peak region (region with highest fire density in fire hotspot) for a given fire season was assessed with regard to annual rainfall of the previous rainy season. Analyses included diachronic (i.e. the variation over time, through the entire study period) and synchronic (i.e. the variation in each main fire hotspot for the same period) evaluations.

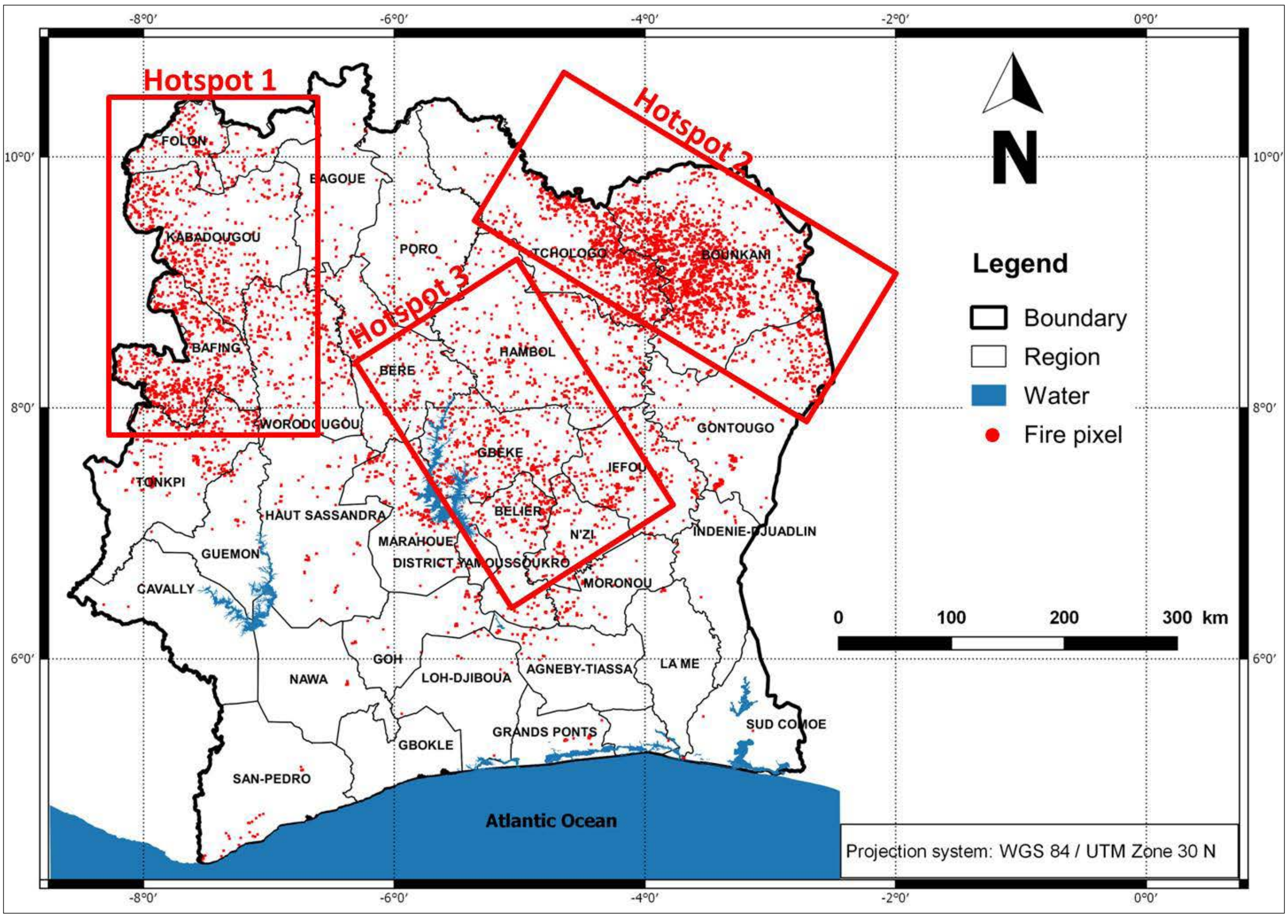

Figure 2: Map of the spatial distribution of active fires in Côte d'Ivoire showing main fire hotspots.

Potential relationships of fire variables with annual precipitation values were also explored. Precipitation data (from 2006 to 2015) was provided by the national meteorology company (Sodexam) and was used to investigate links between fire dynamics and rainfall in main fire hotspots.

Results

Fire spatial activity

Active fires spatial distribution

Active fires were more abundant in the North than the South, visible on the fire map made with 100% confidence fire pixels (Figure 2). The number of active fires ranked in decreasing order revealed regions with higher fire occurrence (Figure 3). Over the 10 years of the study, the country average number of MODIS active fires was 1279±95. The average fire number varied across administrative regions, from 78±11 (Gboklé region, South) to 6047±335 (Bounkani region, North-East). Also, regions such as Bounkani, Tchologo, Hambol, Gontougo (in the North-East), Kabadougou, Bafing, Worodougou, Folon, Tonkpi (in the North-West), Poro (in the North) and Gbêkê, Béré, Bélier (in the Centre) recorded above-average fires. For the Southern regions that had below-average fires, most recorded more than 100 active fires per year in average (Figure 3). This was the case of Gôh (281±54), San-Pedro (253±36), Lôh-Djiboua (190±32), Guémon (150±26), Sud-Comoé (139±14), Grands Ponts (136±15), Cavally (125±17), Indénié-Djuablin (120±15) and Mé (109±15).

Fire density variations

The national average fire density was 0.11±0.01 fires/km^2/year. Fire densities varied greatly by region, however. When ranked in descending order using the 10-year data set (Figure 4), the Nawa region located in the South-West, had the lowest fire density (average 0.01±0.00 fires/km^2/year) whereas the Bafing region in the North-West recorded the highest (0.4±0.02 fires/km^2/year). Based on the comparison to the national average, among the 33 administrative subdivisions of the country, only 11 (located between 2°30'–8°30'W and 7°00'–10°30'N) were identified as prone to fire.

From these results, the 11 fire-prone regions were grouped into three main fire hotspots as high-risk contiguous areas. These three main fire hotspots were designated (from highest to lowest fire densities) as: North-Western, North-Eastern and Central hotspots (Figure 2). The North-Western (also designated as hotspot 1) is in Sub-Sudanian and Sudanian savannas, and includes the regions of Bafing, Kabadougou, Folon and Worodougou. The North-Eastern (hotspot 2) is in Sudanian savannas and includes the regions of Bounkani and Tchologo. The Central (hotspot 3) is located between Sub-Sudanian and forest-savanna areas and includes the regions of Hambol, Gbêkê, Bélier, Béré and Yamoussoukro district (Figure 2).

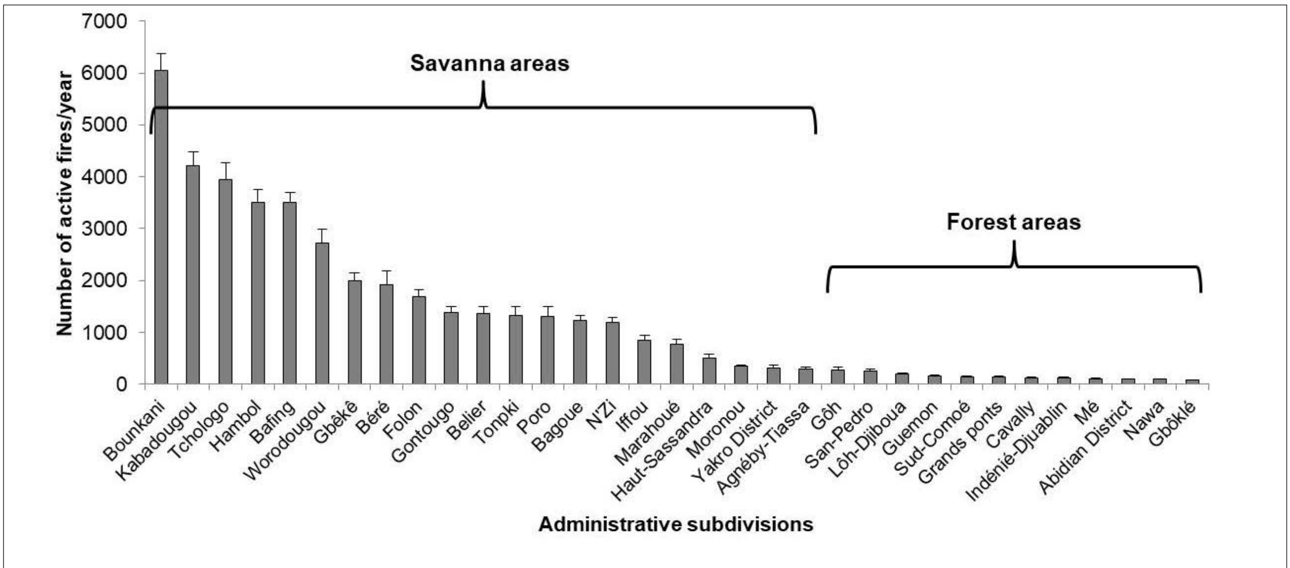

Figure 3: Average number of active fires per year in administrative subdivisions of Côte d'Ivoire over a 10-year period (2007 to 2016).

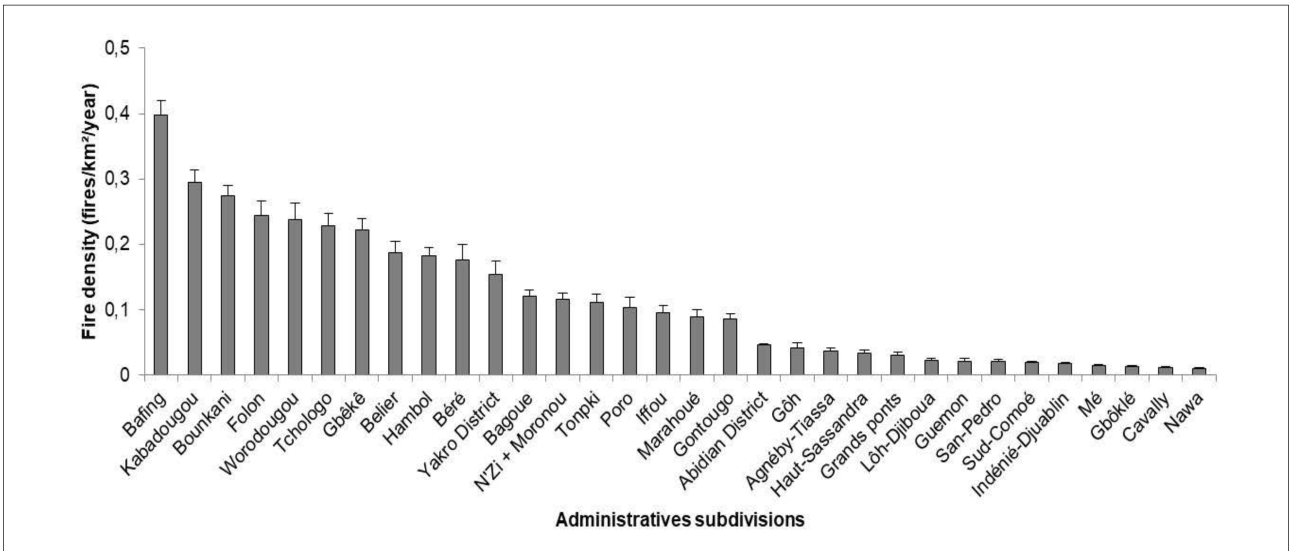

Figure 4: Average fire density per year in administrative subdivisions of Côte d'Ivoire over a 10-year period (2007 to 2016).

Fire temporal activity

Inter-annual variability of fires

At a national level, fires are present in Côte d'Ivoire about 205 days in a year. Over the 10 years of the present study, there was a slight decrease in the total number of fire days (Figure 5a; slope = about -2 days/year, t=-2.77, p=0.024, significant at 95% confidence level). Nevertheless, above-average numbers, i.e. higher numbers of fire days than the national average (205±3 days), were recorded in 2008, 2009, 2010 and 2012. The maximum of 217±5 and the minimum of 191±4 fire days were recorded in 2009 and 2016, respectively.

The number of active fires showed a similar trend to the number of fire days, with a steeper slope (Figure 5b; slope = about -2918 fires/year, t=-5.63, p=0.0004, significant at 95% confidence level).

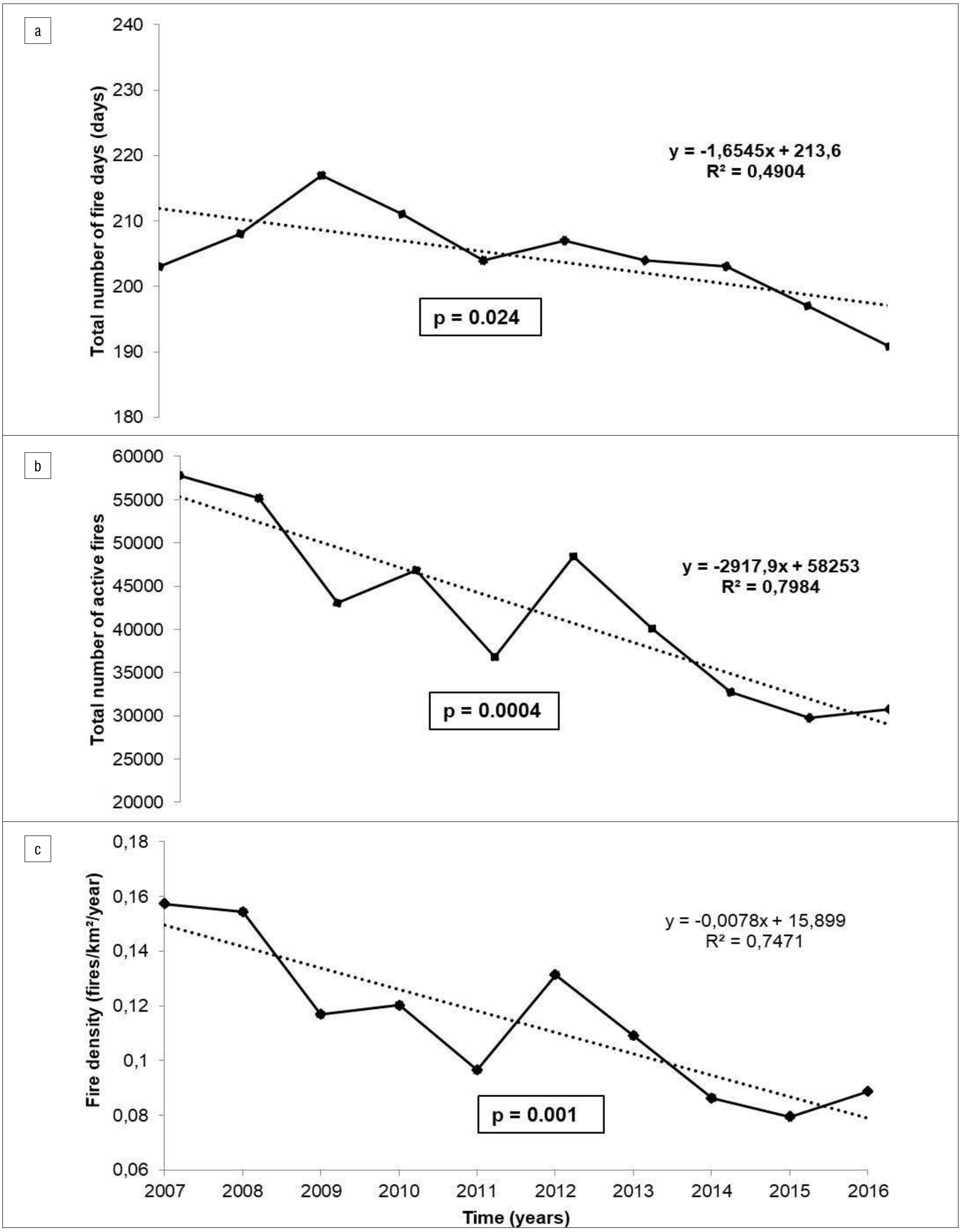

Figure 5: Yearly fire events in Côte d'Ivoire from 2007 to 2016: (a) total number of fire days; (b) total number of active fires; (c) fire density per area.

Over the 10 years, total active fires varied from 29 838±207 fires (2015) to 57 851±330 fires (2007), with 42 205±3226 fires as the annual average. A return time from 1 to 4 years was determined between years with above-average active fires (Figure 5b).

In general, the years from 2007 and 2010 had above-average numbers of active fires, whereas the years between 2013 and 2016 had below-average numbers. In 2011 (the middle of the study period), a below-average number was also recorded, although this number increased the following year (2012) to higher than the national average (Figure 5b). The highest fire peak and the lowest were observed during the 2007/2008 and 2015/2016 seasons, respectively (26 266 and 11 005 active fires, respectively).

For fire density, a similar trend was observed (Figure 5c; slope = about -0.01 fires/km²/year, t=-4.91, p=0.001, significant at 95% confidence level). There was also a return time from 1 to 4 years with above-average values. Fire density varied from 0.08±0.02 fires/km²/year (2015) to 0.16±0.02 fires/km²/year (2007), with a national average fire density of 0.11±0.01 fires/km²/year.

Fire seasonality

For the country as a whole, fires occur across a range of 7 months, from October to April, during the dry season (Figure 6). The same fire period was found in two of the hotspots that we identified: the Bafing (North-West) and Hambol (Centre) regions, whereas it was shortened from October to March in Bounkani (North-East) region (Figure 7).

Most fires occur between December and February, at both the national level and in each of the three fire hotspots. Fire occurrence during these three months was about 91% in Bafing region as at the national level, while it reached 95% and 96% in Bounkani and Hambol regions, respectively.

At national level, the peak month of fires was January (Figure 6), representing 39% of fire annual occurrence vs. about 36% in December and 16% in February. In Bafing region (North-West), fire peak was also in January with 41% of occurrence vs. 27% in December and 23% in February (Figure 7a). In contrast, Bounkani and Hambol regions (North-East and Central) experienced their fire peaks a bit earlier, in December (Figure 7b and 7c, respectively). Peak values were 62% in December vs. 26% in January and 7% in February for Bounkani, and 44% in December vs. 38% in January and 15% in February for Hambol.

Relation between fire density and rainfall in the main fire hotspots

Fire density peaks for the North-Western, North-Eastern and Central hotspots are shown in Figure 8: Bafing (Figure 8a), Bounkani (Figure 8b) and Hambol (Figure 8c). The average fire densities are 0.4±0.02, 0.28±0.02 and 0.18±0.01 fires/km²/year, respectively, for the North-Western, North-Eastern and Central fire hotspots. All three of these hotspots recorded above-average fire density, compared to the national yearly average of 0.11±0.01 fires/km²/year.

Further, the synchronic analysis (fire density and rainfall of the same year) within the main fire hotspots revealed that fire density was negatively correlated to annual rainfall overall, between 2007 and 2016 (Figure 8). That is, low rainfall resulted in high fire density. For each individual site, correlations between low rainfall and high fire density were significant for Bafing region only (Figure 8a; r=-0.96, p<0.0001). This significant negative correlation occurred in Bafing region where the 10-year average rainfall (1046 mm/year) was higher than that of Bounanki and Hambol regions (897 and 886 mm/year respectively).

Importantly, however, fire density was positively correlated with rainfall in the previous years, using diachronic analysis of rainfall from 2006 to 2015 with the fire density from 2007 to 2016 (Figure 9).

Discussion

Fire spatial distribution

The decreasing fire occurrence from the northern to southern regions of Côte d'Ivoire are most likely functions of gradients in rainfall and vegetation distributions from Sudanian (North) and Guinean (Centre) savannas to evergreen forests (South).[24] Indeed, the northernmost savanna areas are dominated by a well-developed herbaceous stratum which constitute the main fuel during fires. Such a relationship of precipitation, vegetation structure, herbaceous fuels and fire occurrence is similar to the demonstrated roles of vegetation structure and fuel chemistry in fire regimes in South Africa by Van Wilgen et al.[27]

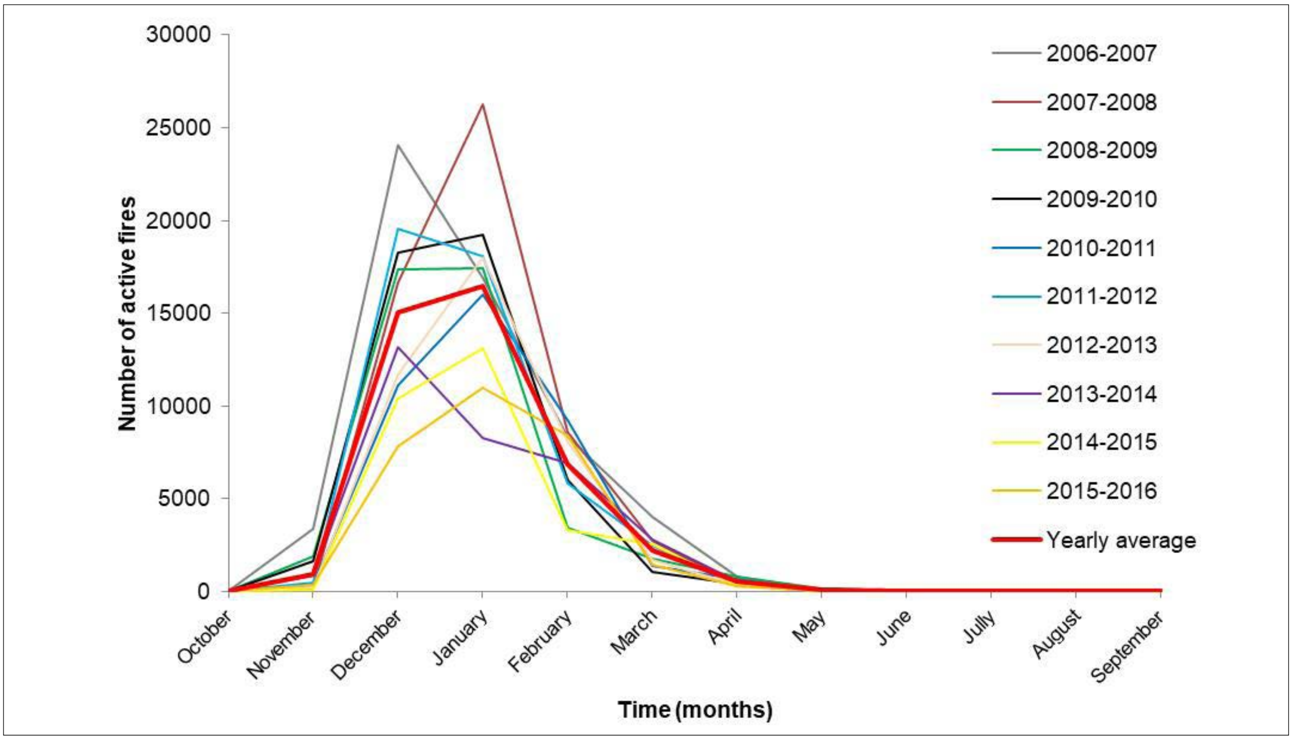

Figure 6: Temporal distribution of active fires in Côte d'Ivoire by month from 2007 to 2016.

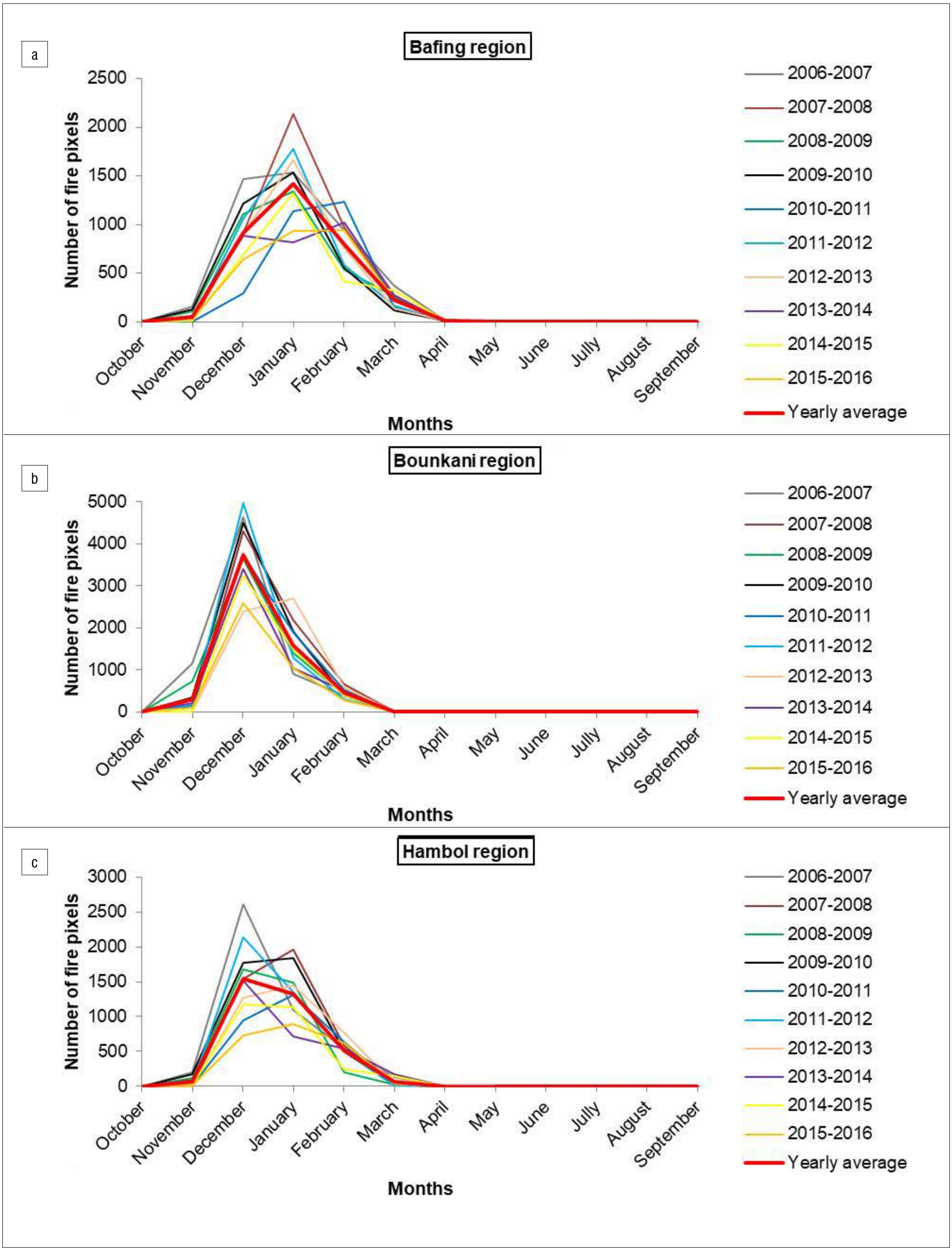

Figure 7: Temporal distribution of fire occurrence by month in the three main fire hotspots: (a) Bafing, main region of the North-Western hotspot; (b) Bounkani, main region of the North-Eastern hotspot; (c) Hambol, main region of the Central hotspot.

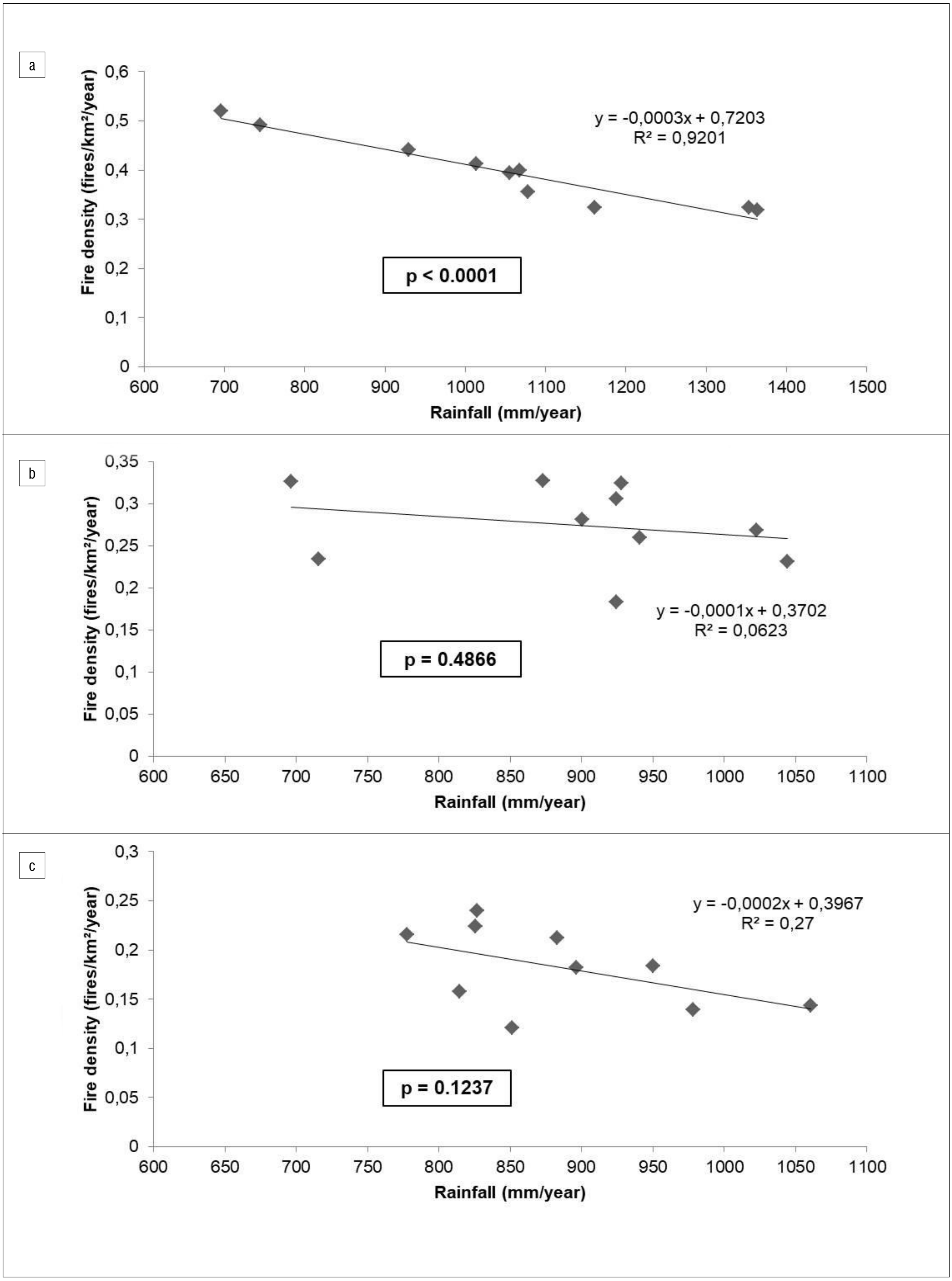

Figure 8: Synchronic variation of fire density relative to precipitation in the three main fire hotspots from 2007 to 2016. (a) Bafing, main region of the North-Western hotspot; (b) Bounkani, main region of the North-Eastern hotspot; (c) Hambol, main region of the Central hotspot.

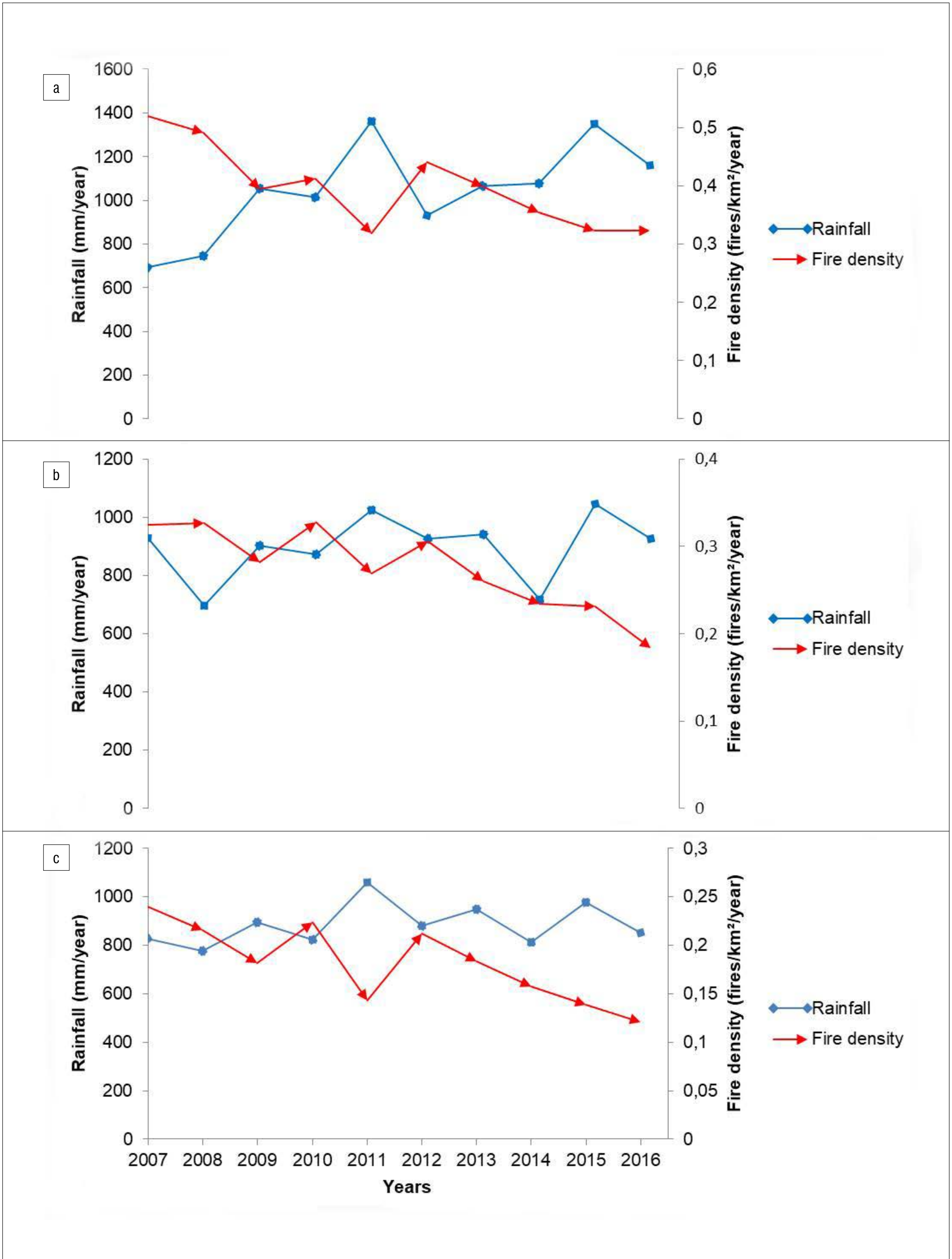

Figure 9: Diachronic variation of fire density (2007 to 2016) and precipitation in the previous wet season (2006 to 2015) in the three main fire hotspots: (a) Bafing, main region of the North-Western hotspot; (b) Bounkani, main region of the North-Eastern hotspot; (c) Hambol, main region of the Central hotspot.

The geographical locations of the three main fire hotspots we identified in Côte d'Ivoire are consistent with a regional study of fires in West Africa by N'Datchoh et al.[11], using burned area from the SPOT VEGETATION product between 2000 and 2007. In their map of vulnerability to fire over West Africa, they stressed that fires were mostly important over Sudanian and Guinean savannas in areas located in southeast Burkina Faso and the northern part of the Côte d'Ivoire–Ghana border (in which the Bounkani region lies). Our study used data over 10 years and fire pixels with 100% confidence of detection over the entire country, so we were able to explore local high-risk areas at greater depth.

The three main fire hotspots of Côte d'Ivoire are spatially distributed in a V-shape, similarly to Ivorian savanna's spatial distribution known as the V-Baoulé.[24] Thus, the heterogeneity of the fire spatial distribution is strongly related to the ecoregions of Côte d'Ivoire. Indeed, the North-Eastern fire hotspot is located in the Sudanian area where grasslands and shrublands are predominant, while the North-Western hotspot is extended from Sudanian to mountain areas composed of woodland savannas and mountain forests. The Central hotspot is located between sub-Sudanian and mesophilous areas in which humid savannas and semi-deciduous forests are mixed.[24]

No fire hotspot was found in the ombrophilous area dominated by evergreen forests. However, this does not mean that this area is sheltered from accidental fires. The most forest regions such as Gôh, San-Pedro, Lôh-Djiboua, Guémon, Sud-Comoé, Grands Ponts, Cavally, Indénié-Djuablin and Mé recorded more than 100 active fires per year on average, despite the fact that forest canopy, cloud cover or thick smoke can completely mask a fire so that it may not be detected by MODIS.[25] This fact presents a challenge to forest protection services which are charged with preserving the remaining forests of the country. They have to use other methods to facilitate large-scale monitoring to reinforce forest surveillance.

Temporal variations of fire activity

Fires occurred in Côte d'Ivoire over more than half the year (205 fire days, 56% of the year). The 7-month fire period for Côte d'Ivoire is much longer than the 93 fire days in Togo (West Africa) reported by Afelu[28] for the period between 1995 and 2014. We suggest the difference may be due to two factors: (1) fire management policies of Togo identify appropriate periods and dates of biomass burning according to ecological regions each year whereas such policies do not exist in Côte d'Ivoire; (2) the land area of Togo is one-sixth the size of Côte d'Ivoire and thus Côte d'Ivoire has a wider range of timing (onset and cessation) and length of fire seasons. Such differences and results here suggest that considerable efforts are needed to develop effective fire management policies in Côte d'Ivoire.

The fact that the maximum number of both active fires and fire densities were recorded during the 2006/2007 season could be related to large-scale climate factors (as well as local conditions). In the decade considered in our study, the year 2006 was classified as the warmest La Niña year.[13] Such an event produces increased air temperatures and higher rainfall which, in some areas, stimulates the growth of combustible biomass. High biomass production in one year has the potential to produce higher fire occurrences during the following year or soon thereafter.[29]

Indeed, in our study, inter-annual variations in both number of active fires and fire density showed a return time of 1 to 4 years with above-average values, meaning high fire activity in the country in these years. Such a return time may indicate the reconstitution rate of vegetation cover (i.e. combustible biomass) after intense fires.[28] Intense fires in a given year may decimate biomass, which might take 1 to 4 years to optimise its resilience and recover sufficient biomass for future intense fire occurrence. This finding is consistent with other studies that suggested that African savannas burn every 2 to 3 years.[11,30]

We do not know to what extent the high numbers of active fires recorded in our study could have been due in part to human-induced fires which increased during the socio-political crisis in Côte d'Ivoire from 2002 to 2011. During this time, particularly in the Central and Northern regions of the country, fire practices may have been intensified without fire management services to limit the local use of fires. Such a socio-political role in fire occurrences is also suggested by the decrease in fire activity and fire density after 2011 – a time which corresponds with the end of the socio-political crisis and a return to normal management conditions.

Several studies have predicted that global climate change will increase both the risk of extreme fires[12] and of fire frequency[13], due to changes in biomass availability and meteorological conditions during fires. In the long term, global climate must be taken into consideration when managing and preventing fires in Côte d'Ivoire. The study reported here will serve as a baseline in monitoring future changes in fire regimes.

Fire season and peaks

The 7-month fire season we describe for Côte d'Ivoire (October to April) is similar to the fire season described by Dwomoh and Wimberly[22] which occurred from November to May in West Africa. In both cases, there was some variation in seasonal patterns across ecoregions. Within this fire season, most fires (91%) occurred from December to February, which is consistent with the pattern reported by N'Datchoh et al.[11] who found that 95% of annual burned areas burned between November and February in West Africa. The single lengthy fire season is strongly associated with the weather patterns caused by the southward movement of the ITCZ (monsoon retreat) over the region.[11,23] In contrast, for South Africa, there are two main fire seasons per year, due to different climatic conditions.[13]

Within the long fire season described for the country as a whole, we identified three main fire hotspots when fire occurrence was the maximum between December and February. There were slight differences in timing and fire activity among the three hotspots, most likely due at least in part to different climatic conditions among the sites. The burned areas are mainly composed of grasslands and shrublands. Anthropogenic pressures exerted by human populations through slash-and-burn agricultural practices, livestock breeding, and hunting contribute to burning during December and January.[31] During these months (the heart of dry season), biomass dries more quickly, thus fostering rapid combustion.[31,32]

In the North-Eastern area, the dry season is very pronounced[23,24] and begins earlier than in the other hotspots; hence, the fire peak in December. The Central fire hotspot is located in a transition zone between the sub-Sudanian and forest-savanna areas, which may explain why fire activity shows characteristics with both the North-Western hotspot (length of fire season) and the North-Eastern hotspot (peak month). Although our study suggests that climate may regulate fire occurrence through precipitation and its effect on biomass production, weather parameters such as air humidity, air temperature and wind speed, which can influence fire propagation on a local level[11,31], were not addressed in this study.

Fire density in the main fire hotspots

Rainfall seemed to be the main driver of fire density (fires per area). Although fire is mainly an anthropogenic phenomenon in West Africa[11], climate regulates the quantity and state of biomass which is mainly the fuel for vegetation fires. The negative correlation between fire density and rainfall in synchronic analysis suggests that high rainfall leads to high moisture content of fuel, creating unfavourable conditions for rapid fire spread, and therefore less intense fires.[31] This negative correlation between fire density and rainfall of the same year could be caused by the influence of precipitation exceeding a certain threshold.[33,34] Indeed, Mbow et al.[34] found a precipitation threshold of about 800 mm/year, above which this influence is observed. In our study, the negative influence of rainfall on fire density was observed only in the Bafing region in forest-savanna area with about 1046 mm/year. In Bounkani and Hambol regions located in the Sudanian area where rainfall was relatively low (897 and 886 mm/year, respectively), this negative correlation was not observed. In our study, this rainfall threshold seemed to be about 900 mm/year.

It is certain that wet seasons control the biomass density and availability (fuel loads) which are limiting factors for fire propagation.[32] Further, we know that the relationship between fire during a dry season and precipitation is not linear.[11] Indeed, in our study, the diachronic analysis of rainfall with regard to fire density revealed that variations of fire density may depend on rainfall of the previous years. The best explanation for this finding was that the above-average values in fire statistics were observed from 1 to 4 years, which means that an increase in rainfall of the 1 to 4 preceding years resulted in an increase in fire activity. Similar findings were found for other African savannas, where rainfall in preceding years resulted in an increase in burnt area.[2,35]

In the three fire hotspots, fire density was higher than the national level, particularly in the North-Western and North-Eastern areas where fire densities were respectively more than triple and double the national average. Therefore, because high fire density can reflect the level of fire risk, fire impacts on regional and local scales can be severe and catastrophic, respectively, even if at global scale their effects are small.[10] This suggests that fire managers and decision-makers should focus on these high-risk areas (main fire hotspots) for better and optimal fire management resources provision during the dry season.

Conclusion

This study provides an insight into fire activity over the past decade in Côte d'Ivoire, identifying the high-risk areas and fire seasons. Three main fire hotspots were identified in savanna areas located in the North-West, the North-East and the Central parts of the country; thus, savanna areas burned more frequently than forest areas. The majority of fires in Côte d'Ivoire occur between December and February. Fire density seemed to be impacted by the amount of the previous year's rainfall with a return time of above-average fires (from 1 to 4 years) evident in fire statistics. A decreasing trend was observed in fire activity across the 10-year study period, most likely associated with temporary socio-economic factors. Indeed, the continuing extent and timing of the wildfire phenomenon require considerable efforts in fire management in Côte d'Ivoire. By identifying the main fire hotspots, their fire season and their fire peaks, this study can assist in the efficient allocation of financial, technical and human resources according to local conditions. The study may also assist decision-makers and institutions managing fires, such as the National Committee for Forest Protection and Fight against Wildfires, to prevent destructive bushfires. The study can serve as a base to assess the effects of both climatic parameters and vegetation types on fire dynamics in the fire hotspots of the Côte d'Ivoire.

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Competing interests

We declare that there are no competing interests.

Authors' contributions

T.D.S.: Original formulation; design of methodology; data collection; data analysis; validation; data curation; writing – the initial draft; writing – revisions; funding acquisition. M.K.: Original formulation; design of methodology; validation; writing – revisions; student supervision; project leadership. A.B.N.: Original formulation; design of methodology; validation; writing – revisions; student supervision; project management. N.E.T.: Design of methodology; validation; writing – revisions.

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