Earth Syst. Dynam. Discuss., 3, 1021–1053, 2012
www.earth-syst-dynam-discuss.net/3/1021/2012/
doi:10.5194/esdd-3-1021-2012


Earth System Dynamics Discussions



# Effects of climate variability on Savannah fire regimes in West Africa

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Received: 7 June 2012 – Accepted: 30 August 2012 – Published: 7 September 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

## Abstract

Bushfires are recognized as environmental processes that affect the atmosphere by the gases and particles emitted and have an ecological and climatic impact. However, there are still numerous uncertainties, particularly about the variability of fire occurrence on the intra- and inter-annual scale. Our objective was to distinguish the space-time variability of fires in West Africa through analysis of burned areas using SPOT VEGETATION from L3JRC (1 April 2000 to 31 March 2007) which were obtained from the modification in the algorithm of cells from the GBA 2000 project. We also analyzed the influence of several large scale factors such as the ENSO, SOI, NAO and the north-south Atlantic temperature gradient factor (SSTG) on the variability of the span of burned areas. Based on areas burned monthly, we calculated the frequency of fire passage on the same pixel. This helped characterize the activity of pixels and distinguish the most vulnerable zones (with a lot of fire activity) from the least vulnerable ones (with less activity). Using a correlation calculation, we also found the influence of the quality of precipitations during preceding rainy seasons on burned areas during the dry season along with climate factors such as MEI, SOI, NAO and the SSTG.

## 1 Introduction

Biomass combustion is an ecological and anthropic phenomenon influenced by the climate. It has an impact on biogeochemical cycles on a local and global scale. There are numerous reports that are reliable indicators of this phenomenon that estimate that over the past few years burned vegetation is on average between 3.5 million to 4.5 million $km^2$ with carbon emissions caused by a third of fossil hydrocarbon combustion (Tansey et al., 2004a,b; Van Der Werf et al., 2006). In Africa, savannahs burn regularly and their tendency to burn can be largely explained by the seasonal irregularity of precipitations that give rise to a wet season and a dry season during which plants become senile and thus more vulnerable to fire. The alternating wet and dry seasons



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in the African savannah predisposes them to burning. The coexistence of grassy and tree vegetation and the close connection between the savannah and fire also contribute to the originality of this biome (Hochberg et al., 1994; Gignoux et al., 1998). Biomass combustion is at the origin of a local phenomenon and becomes a global one when combined with the role of the atmosphere that participates on two levels. The atmosphere transports combustion products over long distances and depends on the nature of the chemical species, atmospheric stability and the intensity of the combustion (Damoah et al., 2004). The atmosphere is also involved in synchronizing fire season conditions, distanced by the mechanism of teleconnection brought on by the climatic mode. The best-known of these climate mechanisms is the El Niño Southern Oscillation (ENSO), however similar roles have been attributed to the North Atlantic Oscillation (NAO) (Parta et al., 2005), and the Atlantic Multidecadal Oscillation (AMO) (Kitzberger et al., 2007).

Our objectives were to study the variability on the space and time scale (inter-annual and intra-seasonal) of fires on west African savannahs, to identify the major fire sources and characterize them in terms of activity and study the influence of local and large scale climate factors on fire regimes in West African savannahs. In order to meet these various objectives, we used data of burned areas from the SPOT VEGETATION satellite obtained from the L3JRC (Tansey et al., 2008) that are data collected daily with spatial resolutions of 1 km × 1 km.

### ENSO-fire relationship

The ENSO represents the most wide scale inter-annual natural climate variation in existence. Anomalies in SST (Sea Surface Temperature) in the east equatorial Pacific Ocean are essentially an expression of this phenomenon. Normal conditions are characterized by hot surface waters in the west Pacific Ocean, while in the east Pacific cold waters rise, all maintained by western winds. The hot phase of the ENSO, El Niño, occurs when trade winds weaken or become inversed due to changes in the air pressure gradient from east to west.





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The effects of the ENSO and its teleconnections are reflected in precipitation and temperature anomalies (Allan et al., 1996). An El Niño event leads to changes in fire practices. These changes vary in different ecosystems. In most tropical ecosystems where NPP (Net Primary Productivity) is high, El Niño brings about droughts. This leads to trees dying, vegetation drying and numerous fires. In semi-arid to arid ecosystems in which precipitation is a limiting factor, an increase in rain due to El Niño is the first result of a surge in productivity, followed by an accumulation of combustible material then returning to normal conditions; during la Niña this combustible dries and becomes extremely inflammable (Holmgren et al., 2006). Fuller and Murphy (2006) reported a high correlation between fire and ENSO indexes like the SOI (Southern Oscillation Index) and a Niño index of 3.4 for forests located between latitudes 5.5° S and 5.5° N. The east African climate is under the influence of the Indian Ocean dipole, which is itself influenced by the ENSO (Black, 2005). According to Lyon and Barnston (2005) the major span of droughts and excessively humid conditions are generally associated with extreme phases of the ENSO.

## 2 Data and methods

### 2.1 Burned area data

In the literature there are several data products listed in connection with fire, the most common are for detecting active fires and burned areas. The first one is based on signals emitted by the leading edge and the second one by the trace left after the fire. Each of these products has its advantages and disadvantages. The burned areas data used in this study was obtained from the SPOT VEGETATION satellite in the L3JRC. The method used for the calculations, using this data is described in Tansey et al. (2008). The data had high spatial (1 km × 1 km) and temporal (daily) resolutions, and was from 1 April 2000 to 31 March 2007. The domain used was West Africa between 0° to 18° N and 18° W to 8° E.





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## 2.2 Linear correlation

This method is widely used in climatology and it consists of calculating linear correlation coefficients measuring the intensity of a relationship between variables. The details of the method are largely discussed by Moore (1979). The square of the correlation coefficient (noted as $R^2$ or determination coefficient) that associates two variables corresponds to the part of common variance between the two variables. However, the validity of the correlation coefficient is founded on the existence of a linear relationship between the two variables studied. A high correlation coefficient does not indicate a causal relationship between the variables.

## 2.3 MEI

To study the effects of the ENSO on the variability of burned areas, we used the MEI (Multivariate ENSO Index) which is calculated using six parameters of the marine surface which are sea level pressure (SLP), the components of the zonal and meridonial flow, sea surface temperatures, temperatures of lower layers and the total cloud cover. Advanced very high resolution radiometers (AVHRR) carried on NOAA meteorological satellites take highly precise measurements of sea surface temperature. Hanley et al. (2003) concluded that MEI are very sensitive to ENSO. According to them, MEI is much more appropriate for global studies whereas other indexes are appropriate for regional level studies. MEI data are available from 1948 until now on the NOAA website (National Oceanic Atmospheric Administration) (NOAA: http://www.cdc.noaa.gov/people/klaus.wolter/MEI).

## 2.4 SOI

The SOI is defined as the pressure difference between Tahiti and Darwin. The slightest variations are measured by the SOI and calculated by various centers. In Australia, the Bureau of Meteorology uses the SOI to determine the ENSO phase in the Pacific.





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The SOI that we used were provided by the NOAA and calculated according to the Ropeleski and Jone (1987) method.

### 2.5 NAO index

The North Atlantic Oscillation is generally described using the NAO index, which is calculated using the difference in pressure at sea level between two meteorological stations located near centers in the Icelandic Low and the Azores High (Hurrell, 1995). When pressure is very low under Iceland and very high over Azores, the NAO index is positive and the difference is very great. The index is negative when the difference is small due to lower intensity of the Icelandic Low and the Azores High.

### 2.6 Atlantic North–South temperature gradient

In the tropical band, atmospheric variability is mainly controlled by large-scale surface conditions. The main modes of climate variation are often described using statistical methods applied to sea surface temperature anomalies. Studies on sea surface temperature records of the Atlantic Ocean have shown the existence of signals with multi-annual and decennial variations specific to the Atlantic Ocean (Fontaine et al., 1998). The natural variation of the two regional modes of variability from the north and on the south and equatorial Atlantic (Bigot, 1997) bring about quasi decennial fluctuations of the meridian gradient of sea surface temperature anomalies of the tropical Atlantic. For this study, we used the temperature data of the north and south Atlantic provided by the NOAA. Using this data, we calculated the temperature gradient between the two regions of the Atlantic and used this gradient to calculate our correlations. This thermal dipole has a significant impact on the variability of precipitations of surrounding continents that is associated with atmospheric circulation on the south and equatorial Atlantic. It also has a major influence on the migration of the ITCZ (Inter-Tropical Convergence Zone) that modulates a large part of tropical precipitations and defines the seasonal cycle of recorded rainfall in regions like West Africa (Fontaine, 1991).





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## 3 Results

### 3.1 Intra-annual variability

Over the course of the same fire year period, we observed variability in the span of burned areas in West Africa. In this part of Africa, the dry season is from October to March; during this period, we observed the presence of fire throughout the entire region. With the dry season, the presence of burned areas revealing controlled biomass fires could be observed. Between the months of November and February, fires are very present over all of West Africa. Between November and February burned areas represent an average of 95.88 % of those burned during the entire year. The peak (about half of the burned areas annually) is reached in December, shown in Fig. 1. Between March and April, the last of the fires can be observed throughout the region.

### 3.2 Inter-annual variability

The results show that the burned areas in West Africa from April 2000 to March 2007 varied between 37 966 $km^2$ (2004–2005) and 104 713 $km^2$ (2000–2001); inter-annual variability can also be observed. Figure 2 shows the burned areas between 1 April 2000 and 31 March 2007. An upward trend of burned areas was also observed between the 2000–2001 and 2002–2003 seasons. However, during the 2003–2004 seasons, a large increase followed by a decrease of areas was recorded. During this period a positive anomaly of biomass fires was observed in 2000 in the northern hemisphere of sub-Saharan Africa (Le Page et al., 2008). From the previous season an upward trend in burned areas can be observed, as presented in Fig. 2.

### 3.3 Spatial variability

Figure 3 presents the spatial and temporal evolution of burned areas in West Africa in climatology for the 2000–2001 and 2004–2005 seasons. It indicates the location of fires in West Africa between 5.20° and 16.81° N latitude and 16.96° W and 7.9° E longitude.





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The spatial variability of burned areas between November and February is characterized by a general displacement from east to west. In November, they are mainly located in the northern part of Benin, the southeast part of Burkina Faso and northern Ghana. In December, they had progressed and were mainly detected in northern Ghana and the north–eastern Ivory Coast. Then in January, burned areas could mainly be observed in the western part of West Africa, i.e. the north western part of the Ivory Coast south of Senegal, whereas in the eastern part they had largely decreased. In February, burned areas considerably decreased throughout West Africa and those observed were mainly located in Guinea, Guinea Bissau, Gambia and the southern part of Senegal. The specificity of the Mali-Senegal part should be noted since a strong presence of fires was observed starting in November for each of the study years. This part of West Africa has high variability in burned areas during the study period.

### 3.4 Frequency of fires

We calculated frequency as follows:

$$F = \frac{N}{T} \quad (1)$$

where $N$ is the number of times a pixel is affected by fires during the study period and $T$ is the study period (year).

The frequency of fire passage on the same pixel is represented in Fig. 4 where each color represents the number of times the same pixel is burned during the study period. Using frequency we deducted the average return time of the fire on the same pixel. Return time is defined as inversed frequency and represents the average time interval between two fires starting consecutively for the same pixel. The return time helped define the different classes for the pixels submitted to our study. We obtained 7 classes of pixels. All pixels in class 1 are those burned just once, thus return times could not be determined and were represented according to the season of fire occurrence (Fig. 5a). These pixels represent 27.93 % of all the pixels burned during the 7-yr study. During





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this period, the evolution of class 1 pixels showed that there were more of the most recently burned areas in the western region, i.e. in Senegal and Mali. The oldest fires are located in the eastern part. Pixels of classes 2 to 7 were represented according to their class (Fig. 5b). From there, a grouping of pixels with a return time less than or equal to 21 months constituted a zone more vulnerable to fire than one with a return time over 21 months. This helped establish a vulnerability map for fire occurrence for West Africa (Fig. 6). Table 1 summarizes the return time of fire for each pixel category as well as the burned area for each class and the portion in percentage for each pixel class. We observed a decrease in areas with frequency. The most vulnerable pixels to fire (with a return time under 21 months) represented 16.41 % with 2 % of these pixels burned every year.

### 3.5 Study of main fire source

Based on the results presented above (Figs. 5a,b and 6), we identified four fire sources that we focused on in this study. These fire sources are geographically located as follows: zone 1 is located between 0.5° and 3° E longitude and 11° and 13° N latitude; it covers north Benin to the south east of Burkina Faso. Zone 2 is located between 0° and 5.5° E longitude and 7.5° and 11° N latitude and covers northern Ghana, the north eastern part of the Ivory Coast and southwest Burkina Faso. Zone 3 is located at 6° and 11° W longitude and 8° and 10° N latitude, it extends from the north west of the Ivory Coast to the south east of Guinea. Zone 4 lies between 9° and 16° W longitude and 11° and 14.5° N latitude, and includes northern Guinea, eastern Mali, Guinea Bissau, Gambia and the south of Senegal (Fig. 7).

For each of these fire sources, we represented the variability of burned areas with inter- and intra-annual scales (Fig. 8). The results show that the peak of fire season for zones generally occurred in November, except for during the 2005–2006 season when the peak occurred in December; the maximum burned areas recorded during the 2003–2004 season was 10 393 $km^2$ and the minimum for the 2004–2005 season was 5751 $km^2$. Daily analysis (Fig. 9) of burned areas in this zone revealed that significant



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areas (> 5 %) were recorded between the 1st and 3rd weeks of detection of the first burned areas (BA), i.e. between the 4th week of October and the 2nd week of November. Fires were present in this zone between the 4th week of October and the 2nd week of November. The fire season lasts between 14 and 26 weeks. The 2004–2005 season lasted for the minimum duration of 14 weeks and the 2006–2007 season lasted the maximum duration of 26 weeks.

For zone 2, peaks were constantly observed in December; the maximum amount of burned areas during the 2000–2001 season was 35 966 $km^2$ and the minimum observed in 2004–2005 was 10 325 $km^2$. Daily analysis of burned areas helped establish that the duration of the fire season varies between 18 and 30 weeks. The minimal duration of fire seasons was recorded in 2000–2001 at 18 weeks and the maximum duration was recorded in 2005–2006. The first detections of BA are carried out between the 2nd and 3rd weeks of November. The most significant areas were recorded between the 1st and 3rd weeks of the first fires, i.e. between the 1st and 3rd weeks of December. The peak generally occurs in January for zone 3 where, during the 2005–2006 and 2006–2007 seasons, peaks were observed in December. In this zone no burned surface was detected in October. The maximum about of burned areas was recorded in 2000–2001 with 15 368 $km^2$ of burned areas and the minimum in 2004–2005 with 4067 $km^2$. The first detections of BA were carried out between the 4th week of November and the 2nd week of December and the 4th week of January.

Zone 4 had high variability in fire peaks between November and January. The maximum amount of burned areas was recorded in 2006–2007 with 21 089 $km^2$ and the minimum in 2004–2005 with 7503 $km^2$. For this zone, it was difficult to determine the duration of fires since they are continually present. The first fires appear much earlier in this zone than in others.

### 3.6 Link between burned areas and precipitation

Our study has shown that for different fire sources, there is an opposition in phases between precipitation and burned areas (data not shown). The four fire sources have





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the same tendency in regards to precipitation. In order to deepen the nature of the link between BA and precipitation, we calculated correlation lags between two parameters, i.e. fire sources at the peak of burned areas for each zone, we calculated correlations around the peak. It resulted in a positive correlation (> 0.6 for zones 1, 3 and 4) between the dry season BA and precipitation during the previous wet season (Fig. 10).

For all zones, curves had the same trend, which means that precipitation has a similar influence on each fire source. The effect of precipitation also depends on the availability of the quantity of biomass, which is combustible for savannah fires.

### 3.7 Effects of large scale climate effects

In order to study the influence of climate factors on burned areas, we calculated the standard monthly anomalies of BA (burned areas) for the seven-year period and we correlated them with month values of the different indexes. Anomalies were calculated using the following formula:

$$A_i = \frac{\mathrm{BA}_i - \overline{\mathrm{BA}}}{\sigma} \tag{2}$$

where is the monthly anomaly $i$, $\mathrm{BA}_i$ the span of the BA of the month $i$, $\overline{\mathrm{BA}}$ the average of BA during the study period and $\sigma$ standard deviation.

Our objective was to study the influence of large scale factors on the variability in the span of BA and identify the months during which this influence was the strongest. Even though the series of data was not long enough to establish rigorous links, we only retained the months where the correlation coefficients were greater than or equal to 0.8 (Tables 2 and 3). This way we eliminated trends between the variability of BA and the climate factors. The results showed that there seems to be a link between the variability of the span of BA and physical phenomena on a global scale. At the beginning of the dry season, the Pacific basin, using the MEI and SOI, tends to influence the span of BA at the inter-annual level in zone 1. The influence of the Atlantic appeared for variability





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at the beginning of the dry season of BA in October. On average, the variability of the span of BA during the dry season in this zone may have been under the influence of the Pacific phenomenon of the SOI.

For zone 2, the variability of BA in October and December seems to have been influenced by phenomena that occurred in the Pacific basin; for December to February there seemed to be an influence of phenomena occurring in the Atlantic with the NAO and SSTG. We also observed that the (variability of BA) in October and December could have been influenced both by phenomena specific to the Atlantic with the SSTG and NAO and to the Pacific with the SOI. On average, in this zone the variability of BA seems to be influenced by the MEI and SSTG.

In zone 3, the influence of the Atlantic persisted throughout the dry season on the variability of BA from November to March through the NAO and SSTG. There appeared to be an influence of the Pacific on BA in February and March. On average, the variability of BA during the dry season appeared to be under the influence of both the Atlantic via the NAO and the Pacific via the SOI.

The variability of BA in zone 4 from October to January seemed to be linked to the Atlantic via the NAO (October and November) and the SSTG (December and January). For BA in January, in addition to the SSTG, there appeared to be the MEI. BA in March seemed to be linked to the SSTG. On average, the BA in this zone was influenced by the SSTG.

This study revealed that, even though fire during the dry season was a purely anthropic activity, the variability of BA could be influenced by physical phenomena such as sea surface temperatures (SST) and sea level pressure (SLP) via their link to the climate. With their effect on the climate, these phenomena bring about additional constraints that could have an effect on the spreading of fire, burned areas and the period when fires start (Van Der Werf et al., 2008).

In zone 1, the results showed that there is a correlation between the variability of BA from October to January and the value of pressure anomalies between Tahiti and Darwin in August, September and October. In August this correlation is negative and in





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September and October, it is positive. BA in October and December were also related to the SSTG in September and November. The correlation between BA in October and those in September is negative and that of BA in November and December is positive. On average in this zone during the dry season, BA were linked to the SOI anomaly in July with a positive correlation.

For zone 2, there could be a negative correlation between the variability of BA from December to February and the July, November and December SSTG. For BA in October, there was a negative correlation with the September NAO and a positive correlation with the June SOI. BA in November were linked to the MEI for the month of November. BA in zone 2 were on average under the influence of the MEI of July and August with which there is a negative correlation. They also are linked to the SSTG in October and November and these correlations are negative.

The variability of BA during the dry season in zone 3 is always related to the NAO index. The BA from November to March were related to the NAO in January, May, June, July, August, September and December. The variability of BA in February and March was also linked to the MEI from September to November, the SOI in June and July and the SSTG in July and August. The correlations between BA and the MEI and between BA and the SSTG are negative. However, there is a positive correlation with the SOI.

At the beginning of the dry season (October and November), BA are linked to the NAO in May and June with a negative correlation. Then, in December, January and March, BA are linked to the SSTG. In January, they are also linked to the MEI with a positive correlation. On average, BA in this zone are linked to the SSTG in October with a negative correlation and in November with a positive correlation.

## 4 Discussion

Analysis of BA in West Africa shows variability in those areas (Fig. 1). This variability, measured intra-annually, can be explained by human activity. In this region of Africa, different social groups coexist and using fire in savannah ecosystems varies with the





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use of lands and social practices. Fires can be ignited late during the dry season to increase their intensity and efficacy in ridding of bushes and young trees. However, fires can be started at the beginning of the dry season to limit the loss of soil nutrients and erosion (William et al., 1998). The goal of starting fires varies according to a person's activity. For example, animal breeders aim to encourage highly nutritious regrowth during the dry season, thus starting fires at the beginning of the dry season.

The results revealed an evolution in BA on the inter-annual scale (Table 1). This evolution showed that the largest areas recorded during the 2000–2001 season were probably favored by the positive anomaly recorded during the previous season (Le Page et al., 2008). This positive anomaly came about with the La Niña conditions between 1999 and 2000. The smallest areas were observed during the 2004–2005 season. This study also showed a spatial variability of BA in West Africa during the study period. As far as the spatial variability of fires is concerned, the configuration of fire spaces is highly influenced by bioclimatic conditions. High precipitation or an absence of precipitation limits the spread of fire. The process of desertification in some regions can lead to the disappearance of fires. For arid ecosystems, using fire also decreases with precipitation (Van Der Werf et al., 2008).

Savannahs frequently have fires because during the dry season, the biomass is dried out and becomes vulnerable to fire (Van der werf et al., 2008). According to studies by Andreae (1991), African savannahs burn every two to three years. Our results have shown that 42 % of West African savannahs burned in this time period.

Even if fires are an essential anthropic activity in this region, the climate regulates the quantity of available dry combustible and its state (ground and combustible humidity, air temperature, wind speed, etc.) for fires to spread. The climate therefore has an impact on the spatial and inter-annual variability of fires (Van Der Werf et al., 2008).

The link between burned areas during the dry season and precipitation is not linear. Precipitation influences the production of biomass, which is the combustible for savannah fires. In arid regions, fires are limited by the density of the available biomass, which is controlled by the quality of the previous wet season (Van Der Werf et al., 2008).





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In most savannah ecosystems, the duration of the dry season is a limiting factor the spread of fires. The amount of combustible is much lower in forest regions. Fires first consume grassy vegetation and the availability of combustible depends on the previous wet season. Normally high rain rates aid in a high rate of primary productivity and a large quantity of biomass during the dry season (Griffin et al., 1983).

The occurrence of an El Niño event is associated with anomalies in atmospheric circulation that are unfavorable to the development of monsoons in the Sudan-Sahelian zone (Poccard, 2000). The influence of the Pacific SST on the variability of BA occurs through precipitation during the wet season. Poccard (2000) showed that when positive anomalies (negative) in the eastern equatorial Pacific (July–September) or the tropical Atlantic (June–October), boreal Africa frequently sees a decrease (increase) in summer rains. The decrease (increase) in precipitation favors a low (high) amount of biomass, which consequently reduces (increases) the span of BA during the dry season. This explains that most positive correlations with SOI during wet season months (June, July, August and September) for zones 1, 2, and 3 and a negative correlation with the MEI.

## 5 Conclusions

Analysis of burned areas between 2000 and 2007 showed spatial and temporal variability within a fire season, i.e. on an intra- and inter-annual scale. Seasonal analysis of burned areas reveals a large increase in areas from November to February (about half of annual fire activity). It also shows that fires are located between 5.20°, 16.81° N latitude and 16.96° W longitude and 7.98° E longitude. On a regional scale, displacement of fire activity from east to west within a fire season was observed, with the exception of zone 4 where there is high variability of burned areas.

Calculating the frequency of fire passage showed that most West African savannahs burn on average every two to three years. This also helps establish a vulnerability map





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for fires where the most vulnerable zones are those with a fire return time less than or equal to 21 months and distinguish four major fire sources (zones 1 to 4).

Studying the influence of local climate factors like precipitation revealed that there is an interaction between them and the variability of burned areas on an inter-annual scale. For each of the four fire source that we studied, there is a link between the quality of the wet season and burned areas during the dry season. It is a nonlinear link since rain influences the availability of biomass that serves as savannah fire combustible. The study showed that there is a positive correlation between dry season fires and rain from the previous wet season. For zones 1 and 2, it is rain in July and August that influences the variability of dry season burned areas the most. For zones 3 and 4, it is respectively the rain in August and September that influences the inter-annual variability of burned areas.

Even though controlled burning is mainly an anthropic activity, it is also influenced by climate. This study revealed that there is an influence of large scale factors on burned areas. It also revealed that a negative phase of MEI is associated with wide spans of burned areas and a large oscillation of small spans of BA. The influence of the SOI translates to a decrease in the span of BA with its few variations and an increase in burned areas during high variations periods. We recorded a decrease in the span of burned areas when an anomaly of the NAO remained positive. It also revealed an influence of the Pacific and Atlantic Oceans on burned areas. The Pacific could have an influence on the variability of the spans of burned areas in zones 1 and 2 via the SOI and MEI, respectively, and the Atlantic via the SSTG. In zone 3, the variability of burned areas during the dry season was influenced by the Atlantic via the NAO and the Pacific with the SOI. Finally, in zone 4, the variability of burned areas was dominated by SSTG control.

*Acknowledgements.* We acknowledge RIPIECSA grant which allowed this work and L3JRC for making biomass burning data available.





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**Table 1.** Return time of fire on pixels burned more than once, their surface area and percentage.

| | Class 2 Pixels burned 2 times | Class 3 Pixels burned 3 times | Class 4 Pixels burned 4 times | Class 5 Pixels burned 5 times | Class 6 Pixels burned 6 times | Class 7 Pixels burned 7 times |
|---|---|---|---|---|---|---|
| Average return time | 42 months | 28 months | 21 months | 17 months | 14 months | 12 months |
| Surface area in $km^2$ | 115 664 | 93 033 | 68 932 | 46 135 | 25 374 | 9898 |
| Portion in percentage | 23.30 | 18.74 | 13.89 | 9.30 | 5.11 | 2 |

**Table 2.** Influence of the SOI, MEI, NAO index and the SSTG on BA variability. Figures represent the index of the month and year, for example 8 is the month of August and 9 the month of September.

| BA | Oct. | Nov. | Dec. | Jan. | Feb. | Mar. | Average |
|---|---|---|---|---|---|---|---|
| Zone 1 | SSTG 9, SOI 8 | MEI 9; SOI 10 | SOI 8; SSTG 11 | SOI 9 | – | – | SOI 7 |
| Zone 2 | SOI 6, NAO 9 | MEI 9 | SSTG 11; | SSTG 12 | SSTG 7 | – | MEI 7; MEI 8; SSTG 10; SSTG 11 |
| Zone 3 | – | NAO 6, | NAO 9 | NAO 5 | MEI 9, 10; NAO 7, 12; SOI 6; SSTG 7 | MEI 10, 11; NAO 1, 8; SSTG 8; SOI 7 | NAO 11, SOI 4, 11 |
| Zone 4 | NAO 5 | NAO 6 | SSTG 6 | MEI 7, 8; SSTG 5 | – | SSTG 8 | SSTG 10, SSTG 11 |





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**Table 3.** influence trend of Pacific and Atlantic basins on the variability of BA. Red represents the Pacific basin and yellow the Atlantic basin.

| Zone | Oct. | Nov. | Dec. | Jan. | Feb. | Mar. | Average |
|---|---|---|---|---|---|---|---|
| Zone 1 | SOI<br>SSTG | SOI<br>MEI | SOI<br>SSTG | SOI | – | – | SOI |
| Zone 2 | SOI<br>NAO | MEI | SOI<br>SSTG | SSTG | SSTG | – | SSTG<br>MEI |
| Zone 3 | – | NAO | NAO | NAO | SOI; MEI<br>NAO; SSTG | SOI; MEI<br>SSTG; NAO | SOI<br>NAO |
| Zone 4 | NAO | NAO | SSTG | SSTG<br>MEI | – | SSTG | SSTG |





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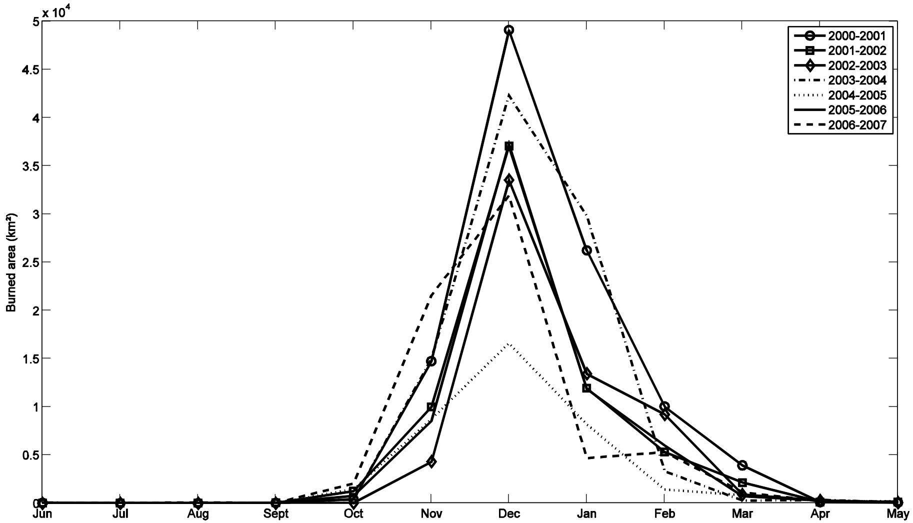


**Fig. 1.** Inter-annual variability of burned areas in West Africa between April 2000 and March 2007.

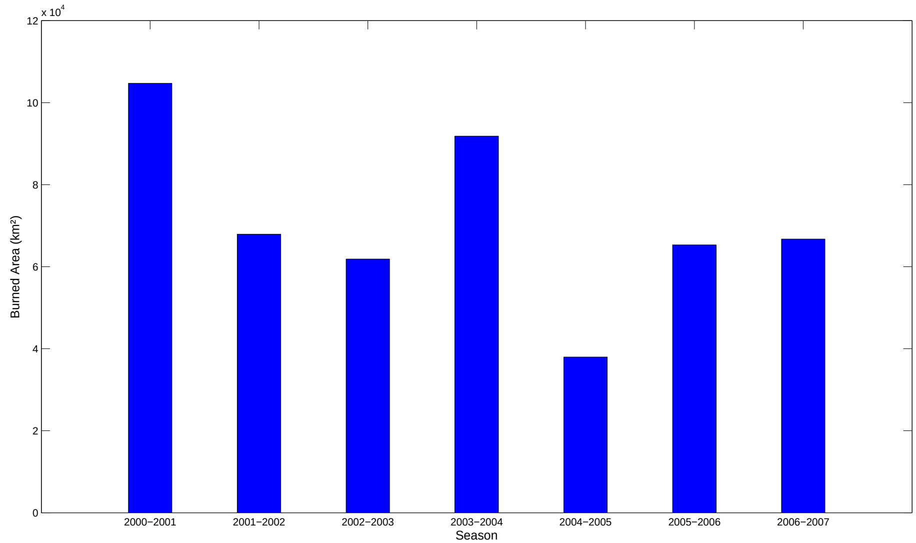


**Fig. 2.** Areas burned annually in West Africa.





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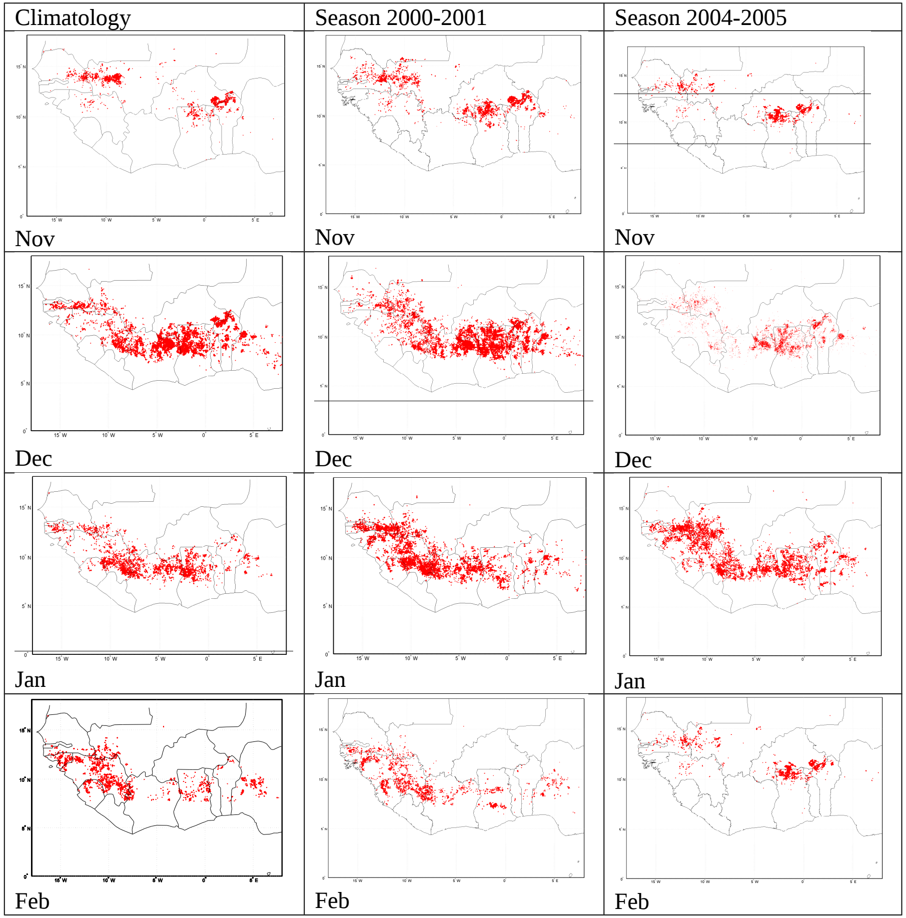


**Fig. 3.** Spatial and temporal evolution of fires during the dry season in West Africa.





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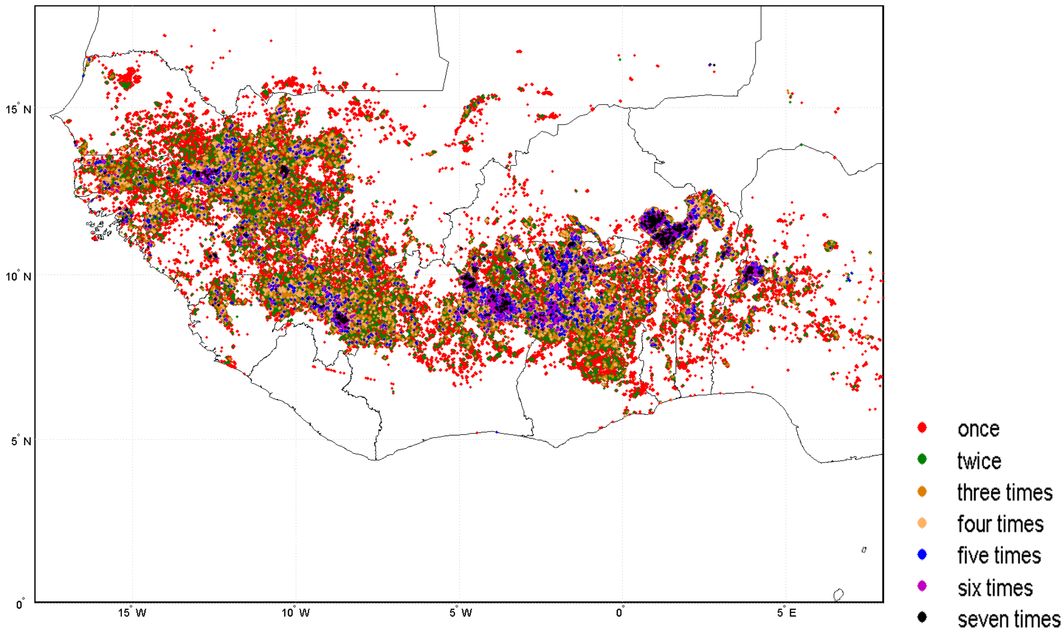


**Fig. 4.** Frequency of fire passage in the same areas during the period of April 2000 to March 2007.





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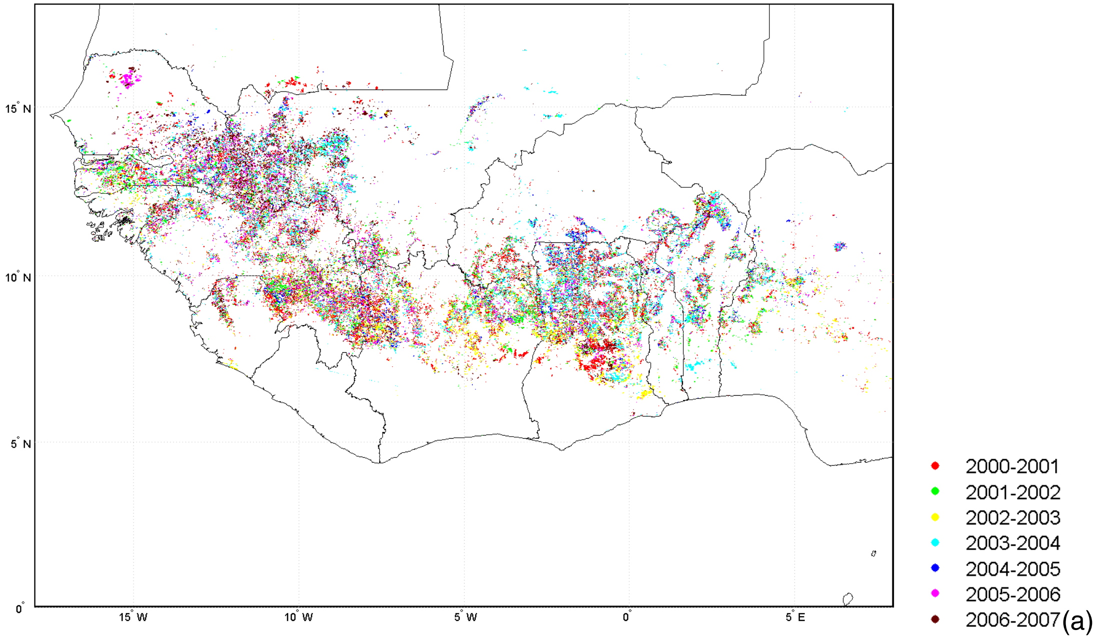


**Fig. 5. (a)** All pixels burned one time over the seven-year study period per season.

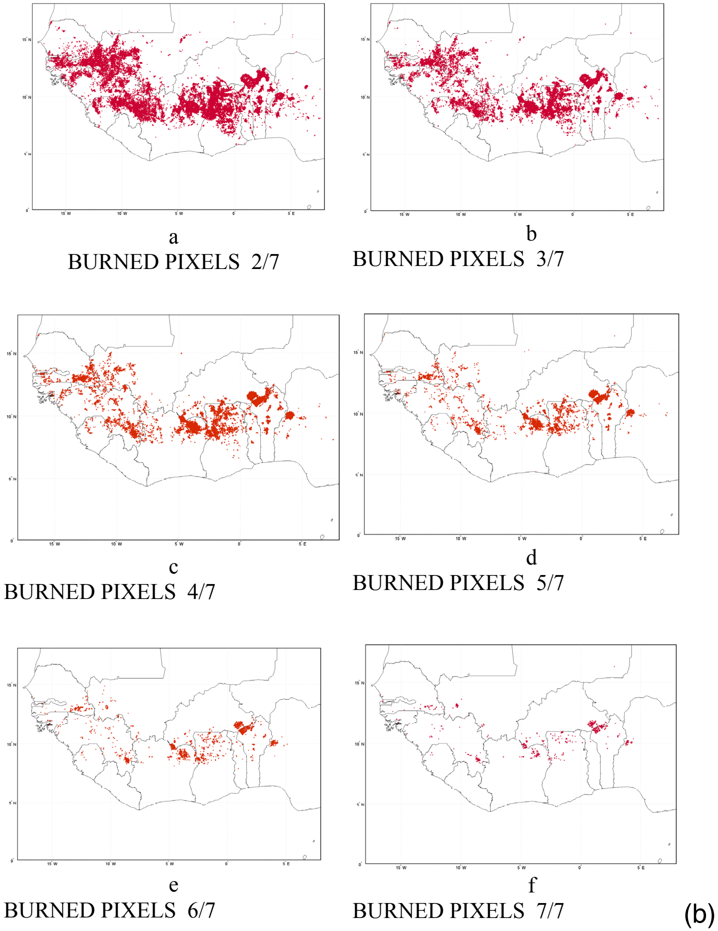


**Fig. 5. (b)** Frequency of fires in burned areas.



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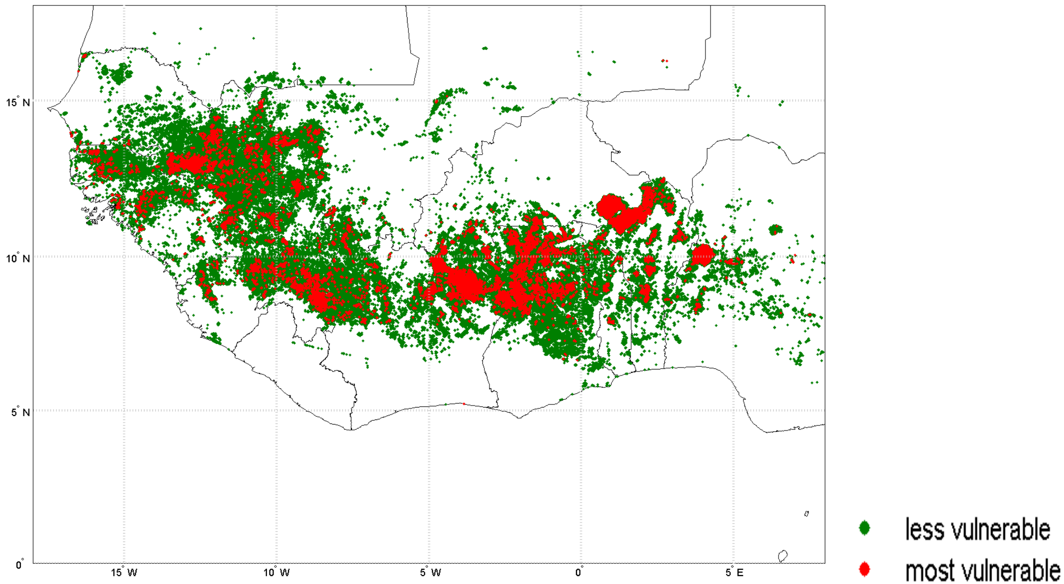


**Fig. 6.** The most vulnerable and least vulnerable zones to fire.





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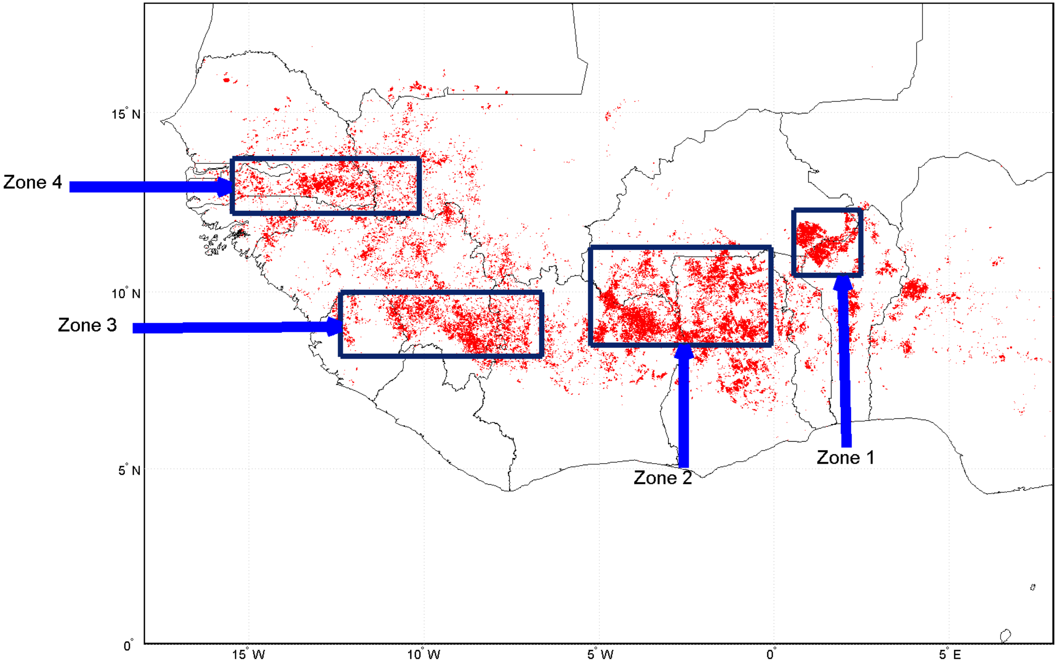


**Fig. 7.** Fire sources in West Africa.





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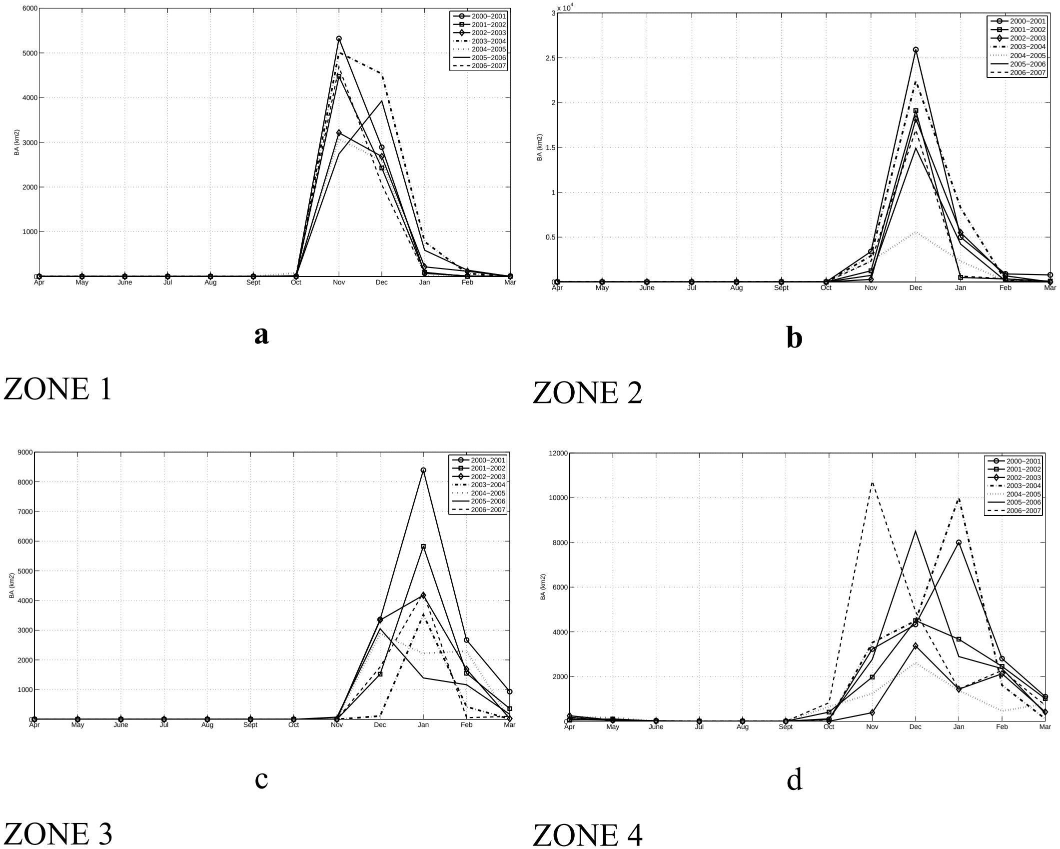


**Fig. 8.** Variability of burned areas in zones in West Africa.





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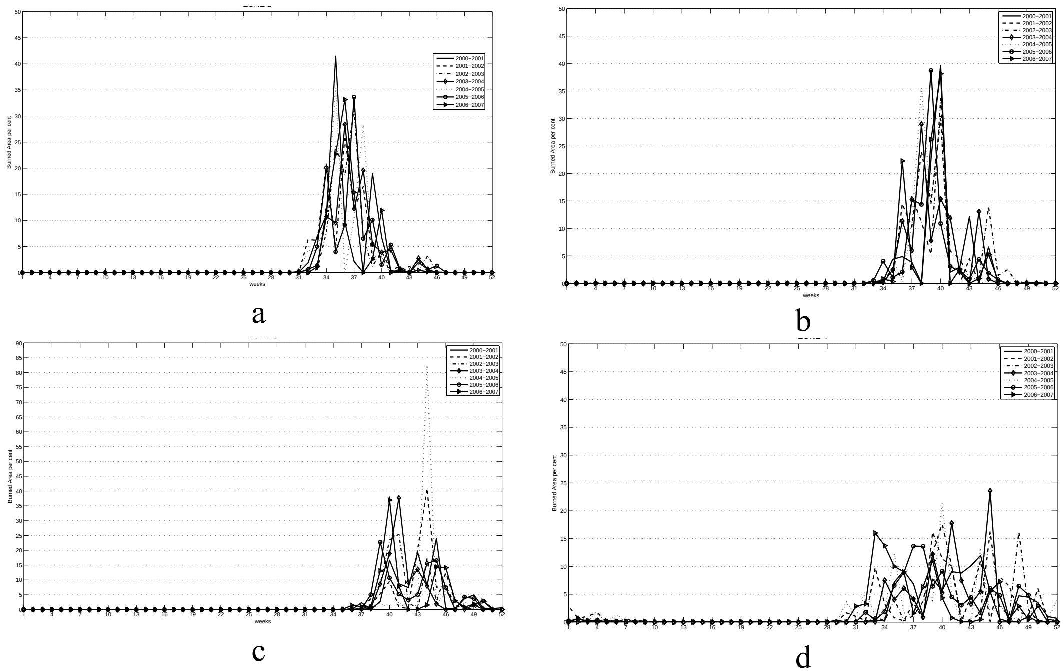


**Fig. 9.** Daily variability of fire sources in zones in West Africa.





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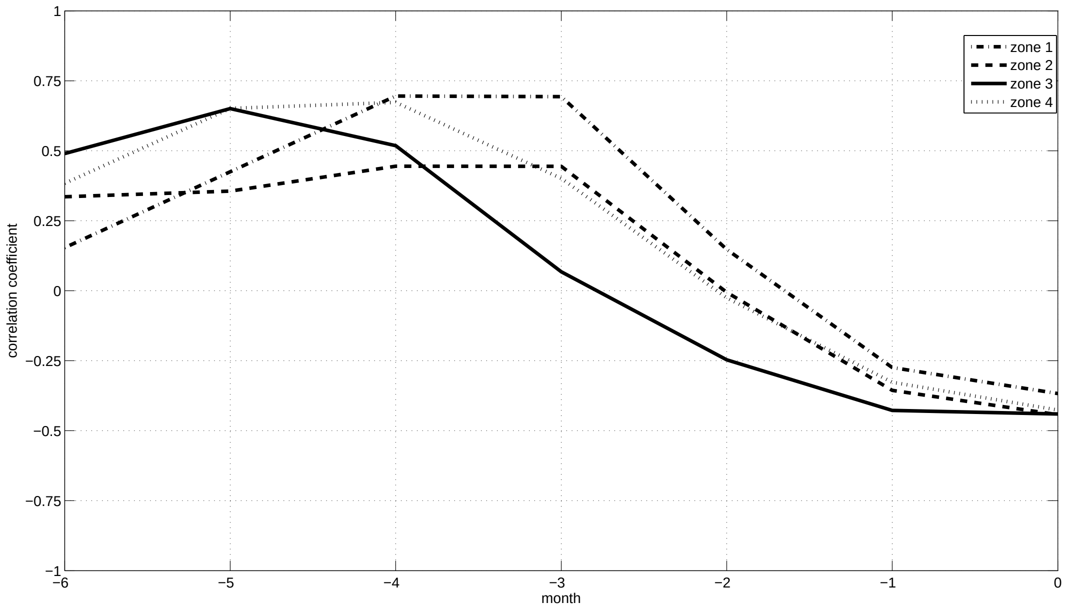


**Fig. 10.** Correlation lag between the span of BA and precipitation.





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