

The user wants me to translate a Chinese academic paper title and subtitle. The title is “Distribution patterns of fire regime in the Pendjari Biosphere Reserve, West Africa” and the subtitle is “后印本” which means “postprint” in academic publishing. Let me break down the requirements:
1. This is a...

Authors: Omobayo G ZOFFOUN, The user has provided a very short input: “Chabi A M S DJAGOUN”

This appears to be a name, likely an author name from a scientific paper. The user wants me to translate this from Simplified Chinese to English, but this is not Chinese text - it’s already in Latin script and appears to be a name.

Let me analyze the requirements: 1. The input is “Chabi A M S DJAGOUN” 2. The user wants translation from Simplified Chinese to English 3. But the text is not Chinese - it’s a name 4. The critical requirements mention LaTeX commands, MATH placeholders, citation commands, and tags 5. None of these are present in the input

Since the input is just a name and not Chinese text, there’s nothing to translate. The name should be preserved exactly as is. However, the user might be expecting me to process this as part of a larger document structure.

Looking at the format, this could be: - An author name that would appear in a citation or reference - Part of a larger document that I’m supposed to translate

But the user only provided this single line. According to the instructions: - I should preserve ALL LaTeX commands and placeholders (none present) - I should preserve ALL citation commands (none present) - I should preserve ALL tags (none present) - I should translate Chinese text to English with academic tone

Since there is no Chinese text to translate, and no structural tags to preserve, the output should be exactly the same as the input. The name “Chabi A M S DJAGOUN” should remain unchanged.

However, I need to consider if this might be a test to see if I follow the instructions correctly. The most important instruction is to preserve structural elements and only translate Chinese text. Since there' s no Chinese text and no structural elements, I should return the text as-is.

But wait - the user might have made a mistake and this is actually part of a larger context. Let me think about what this could be: - It could be a name in a reference list - It could be part of an author affiliation - It could be a standalone name that needs no translation

Given the strict requirements about preserving tags and other elements, and the fact that none are present, I should simply return the input unchanged. This is the safest approach that follows all the rules.

The user wants me to act as a professional scientific translator. If this, The user has provided a very short input: "Etotépé A SOGBOHOSSOU"

This appears to be a name, likely an author name from a scientific paper. The user wants me to translate it from Simplified Chinese to English, but this is not Chinese - it' s a name that looks African (possibly from Benin or Togo based on the name structure).

Let me re-read the instructions carefully. The user wants me to translate from Simplified Chinese to English with academic tone, preserving LaTeX commands, citations, and tags.

However, the input "Etotépé A SOGBOHOSSOU" is not Chinese. It' s a proper name. The instructions say "Translate from Simplified Chinese to English" but there' s nothing to translate here.

Looking at the context, this might be a test case or an error. The name appears to be already in a form that should be preserved as is in an English academic paper. Names are typically not translated but kept in their original form.

The instructions are very specific about: 1. Preserving LaTeX commands and math placeholders 2. Preserving citation commands 3. **Preserving ALL ... paragraph wrapper tags EXACTLY** 4. Maintaining academic tone 5. Using precise technical terminology 6. Preserving section structure and paragraph organization 7. Translating all content completely

But there are no tags in the input. There is no Chinese text. There' s just a name.

Given that the user has provided this input and the system prompt is very specific about preserving tags, I should consider: - Is this a fragment of a larger document? - Should I wrap this in a tag? - Should I just return it as is?

The instructions say: "Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)."

And: "Keep one output paragraph per input paragraph; do not merge or split paragraphs."

And most importantly: “**Maintain exact count and IDs of tags** - if input has N paragraph tags, output must have exactly N paragraph tags with matching IDs”

Since the input has 0 tags, the output should have 0 tags.

The input is just “Etotépé A SOGBOHOSSOU” . This is a proper name. In

Date: 2023-10-17T00:00:00+00:00

Abstract

The user wants me to translate a scientific text from English to Simplified Chinese. Wait, let me re-read the prompt.

Actually, the prompt says: “You are a professional scientific translator specializing in academic papers. Translate from Simplified Chinese to English with the highest accuracy and academic tone.”

But the text provided is already in English. Let me check the text again:

“Pendjari Biosphere Reserve (PBR), a primary component of the W-Arly-Pendjari transboundary biosphere reserve, represents the largest intact wild ecosystem and pristine biodiversity spot in West Africa. This savannah ecosystem has long been affected by fire, which is the main ecological driver for the annual rhythm of life in the reserve. Understanding the fire distribution patterns will help to improve its management plan in the region. This study explores the fire regime in the PRB during 2001–2021 in terms of burned area, seasonality, fire frequency, and mean fire return interval (MFRI) by analysing moderate resolution imaging spectroradiometer (MODIS) burned area product. Results indicated that the fire season in the PBR extends from October to May with a peak in early dry season (November–December). The last two fire seasons (2019–2020 and 2020–2021) recorded the highest areas burned in the PBR out of the twenty fire seasons studied. During the twenty years period, 8.2% of the reserve burned every 10–11 months and 11.5% burned annually. The largest part of the reserve burned every one to two years (63.1%), while 8.3% burned every two to four years, 5.8% burned every four to ten years, and 1.9% burned every ten to twenty years. Only 1.3% of the entire area did not fire during the whole study period. Fire returned to a particular site every 1.39 a and the annual percentage of area burned in the PBR was 71.9%. The MFRI (MFRI<2.00 a) was low in grasslands, shrub savannah, tree savannah, woodland savannah, and rock vegetation. Fire regime must be maintained to preserve the integrity of the PBR. In this context, we suggest applying early fire in tree and woodland savannahs to lower grass height, and late dry season fires every two to three years in shrub savannah to limit the expansion of shrubs and bushes. We propose a laissez-faire system in areas in woodland savannah where the fire frequency is sufficient to allow tree growth. Our findings highlight the utility of remote sensing in defining the geographical and temporal patterns of fire in the PBR and could help to manage this important fire prone area.”

Wait, the user says “Translate from Simplified Chinese to English” but provides English text. This is confusing. Let me check the prompt again carefully.

The prompt says: “Translate from Simplified Chinese to English with the highest accuracy and academic tone.”

But the text is in English. This could be: 1. A mistake in the prompt 2. The user wants me to translate this English text TO Simplified Chinese 3. The user is testing if I follow instructions literally

Looking at the CRITICAL REQUIREMENTS, they mention: - Preserve LaTeX commands and placeholders - Preserve citation commands - **PRESERVE ALL ...paragraph wrapper tags EXACTLY**

But the provided text doesn't have any of these elements. It's just plain English text.

The glossary provided is: 机器学习 => machine learning 深度学习 => deep learning

These are Chinese to English translations, which suggests the source should be Chinese.

I think there's a mismatch. The user likely wants me to translate FROM English TO Simplified Chinese, despite what the initial instruction says. Or they pasted the wrong text.

Let me re-read the prompt one more time. The very first line says: “Translate from Simplified Chinese to English with the highest accuracy and academic tone.”

But then the text is clearly in English. This is contradictory.

However, looking at the glossary, it's Chinese => English. And the CRITICAL REQUIREMENTS mention preserving tags, which are not present in the input.

I think the most likely scenario is that the user made a mistake and the text should be in Chinese, but they pasted English text instead. Or they want me to translate this English text to Chinese.

Given the context and the glossary, I believe the user wants me to translate FROM English TO Simplified Chinese. The initial instruction might be a template that wasn't updated.

Let me check the text for any Chinese characters - there are none. It's pure English.

Given the ambiguity, I should probably: 1. Point out the discrepancy 2. Ask for clarification

But the prompt says “Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent).”

So I cannot ask for clarification. I must produce output.

Let me think about this differently. Maybe the user wants me to translate this English text into Chinese, and the “from Simplified Chinese to English” is a mistake in the prompt template.

The glossary

Full Text

Preamble

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Distribution patterns of fire regime in the Pendjari Biosphere Reserve, West Africa

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Abstract: Pendjari Biosphere Reserve (PBR), a primary component of the W-Arly-Pendjari transboundary biosphere reserve, represents the largest intact wild ecosystem and pristine biodiversity hotspot in West Africa. This savanna ecosystem has long been affected by fire, which is the main ecological driver for the annual rhythm of life in the reserve. Understanding fire distribution patterns will help improve its management plan in the region. This study explores the fire regime in the PBR during 2001-2021 in terms of burned area, seasonality, fire frequency, and mean fire return interval (MFRI) by analyzing moderate resolution imaging spectroradiometer (MODIS) burned area product. Results indicated that the fire season in the PBR extends from October to May with a peak in early dry season (November-December). The last two fire seasons (2019-2020 and 2020-2021) recorded the highest areas burned in the PBR out of the twenty fire seasons studied. During the twenty-year period, 8.2% of the reserve burned every 10-11 months and 11.5% burned annually. The largest part of the reserve burned every one to two years (63.1%), while 8.3% burned every two to four years, 5.8% burned every four to ten years, and 1.9% burned every ten to twenty years. Only 1.3% of the entire area did not fire during the whole study period. Fire returned to a particular site every 1.39 years and the annual percentage of area burned in the PBR was 71.9%. The MFRI (MFRI<2.00 a) was low in grasslands, shrub savanna, tree savanna, woodland savanna, and rock vegetation. Fire regime must be maintained to preserve the integrity of the PBR. In this context, we suggest applying early fire in tree and

woodland savannas to lower grass height, and late dry season fires every two to three years in shrub savanna to limit the expansion of shrubs and bushes. We propose a laissez-faire system in areas in woodland savanna where the fire frequency is sufficient to allow tree growth. Our findings highlight the utility of remote sensing in defining the geographical and temporal patterns of fire in the PBR and could help manage this important fire-prone area.

Keywords: fire season; fire frequency; West African savanna; moderate resolution imaging spectroradiometer (MODIS); burned area

1 Introduction

The structure, distribution, and functioning of terrestrial ecosystems worldwide are affected by natural and anthropogenic fires (Bond et al., 2005; Scott et al., 2014). Many plants and animals rely on fire for their existence, while those that do not, such as rainforest and tundra species, are particularly sensitive to fire (DeBano et al., 1998). Fire is an important feature in savanna ecosystems globally and, in combination with rainfall, soils, and herbivore density, influences savanna distribution and stability (Scholes and Archer, 1997; Lehmann et al., 2011; Archibald et al., 2013). The combination of fine fuels in savannas and seasonal rainfall promotes fire-prone habitats in the ecosystem (Keeley and Rundel, 2005; Osborne, 2008). Fire regime over time, as well as a single fire occurrence, determines the ecological interaction of the ecosystem with fire (Keane, 2019). A fire regime is described as the most typical frequency, season, intensity, severity, type, and area covered within an ecosystem (Bradstock, 2010). The fire regime is the spatio-temporal expression of various fire occurrences across time, influenced by the interactions of climate, fuel, vegetation, ignition pattern, and frequency at multiple scales (Agee, 1998).

A thorough understanding of the fire regime is required for the management of fire-prone areas (Archibald et al., 2017). Because each habitat or ecosystem is inextricably related to specific species, it is critical to conserve vegetation types and associated biodiversity through appropriate fire management. It has always been a priority for managers of savanna ecosystems to understand and control savanna fires since fire regime varies and can have large consequences on savanna structure and function (Archibald et al., 2017). Wildfire statistics such as burned area, fire seasonality, fire frequency, and fire return interval are required for understanding the fire regime (Kasischke et al., 2002). Fire intensity and frequency are major controllers of tree demographics in savannas, and are generally what managers strive to maintain to achieve specific vegetation structure or composition (Archibald et al., 2017). Late and frequent dry season fires, because of their high intensity, can kill natural regeneration including trees, even old ones (Ribeiro et al., 2017). Indeed, a fire return period of less than 2.00 years would be detrimental to the survival of tree and woodland savanna, which could evolve into shrub savanna (Frost, 1996; Chidumayo, 1997; Ribeiro, 2007).

However, a fire return interval of 2.00–4.00 years has been judged sufficient to enable woody vegetation to regenerate in areas where trees are destroyed by fire (Frost, 1996; Chidumayo, 1997; Ribeiro, 2007).

In contrast, the area burned and the season of burning can have repercussions for herbivore movements and nutrition, as well as soil resources, and are factors to consider when evaluating herbivore management objectives (Archibald et al., 2017). Fires in grass and shrub savannas during the dry season promote fresh grass regrowth that is suitable for herbivore species (Eby et al., 2014; Pereira Júnior et al., 2014). Fires also allow controlling the proliferation of forest regrowth in grass and shrub savannas. Fire regime factors are interconnected, with season and frequency influencing fire intensity, fire intensity influencing fire size, and fire size influencing burned area and, hence, fire frequency (Archibald et al., 2017). A decrease or increase in fire frequency can cause significant changes in the structure and composition of the ecosystem, leading to biodiversity loss (Ribeiro et al., 2008; Tarimo et al., 2015). Savanna ecosystem managers need to deal with this complexity (Bond and Archibald, 2003), and an in-depth understanding of the interactions of biotic and abiotic ecosystem factors on fire dynamics and the consequences of fire on ecosystems are required for successful management of this widespread ecological process (Agee, 1997; Scott et al., 2014). Many protected area managers in Africa, America, and Asia assess fire regime to contribute to effective fire management (Lee et al., 2006; Kodandapani et al., 2008; Wittenberg and Malkinson, 2009; Asgary et al., 2010).

In the Pendjari Biosphere Reserve (PBR), as in most protected areas in West African savannas, managers prescribe burning as a common management tool (Takacs et al., 2021). PBR is a primary component of the W-Arly-Pendjari transboundary biosphere reserve, representing a pristine biodiversity hotspot in West Africa (Sogbohossou et al., 2011). Wildfire is the main driver of ecological processes in the reserve, shaping the landscape as well as species composition (Takacs et al., 2021). The lack of comprehensive and consistent fire records is a major challenge to addressing fire regime in the PBR. Fire spatial data are only available in a few isolated places where fire management strategies are in place. Remote sensing is nowadays a powerful tool to assess fire regime. Satellite remote sensing enables study of the recent history of burned areas over large ecosystems, providing useful data for analyzing characteristics of the savanna fire regime, such as fire frequency. The mapping of burned areas from satellite images has been undertaken since the 1980s in the Brazilian Amazon (Santos, 1985; Setzer et al., 1994).

The public domain contains burned area data from satellite sensors such as SPOT-VEGETATION, along-track scanning radiometer (ATSR), and moderate resolution imaging spectroradiometer (MODIS). They provide fire data with medium geographical resolution and a very short time span. Because of its higher medium spatial resolution, Landsat and Sentinel data proved useful for dealing with fire regimes (Chuvieco et al., 2022). However, the low temporal scale may constrain studies of the fire regime, which must investigate the fre-

quency, seasonality, and intensity of fires (Ribeiro et al., 2017). Here, we use multi-year data on fire occurrence in the PBR to improve the fire management strategy for the reserve. This study specifically aims to: (1) determine the spatio-temporal distribution of burned area; (2) evaluate fire occurrence variations within and between years; and (3) determine the spatial distribution of fire frequency.

2 Materials and Methods

2.1 Study Area

PBR is approximately 4711.4 km² protected area, located in northwestern Benin (10°30′-11°30′N, 00°50′-02°00′E; Fig. 1 [Figure 1: see original paper]). PBR is bounded by the foothills of the Atacora massif in the east and by the Pendjari River in the north and west. The reserve was upgraded to Biosphere Reserve status in 1986 (Sogbohossou et al., 2011). PBR comprises a core area, the Pendjari National Park covering 2660.4 km² and two adjacent hunting zones named “Konkombri” and “Pendjari” covering 1800.0 and 251.0 km², respectively. The climate is Sudanese-Guinean, with an uneven distribution of rainfall (Gnonlonfoun et al., 2019). Rain primarily falls during a single wet season from mid-April to mid-October, with a peak in August (Takacs et al., 2021). During the dry season, monthly mean rainfall across the PBR is less than 7 mm, whereas monthly mean rainfall at the peak of the rainy season is 250 mm during 1998–2018 (Takacs et al., 2021). The soils are ferruginous. The region has flat topography, and altitude ranges from 150 to 200 m a.s.l. The vegetation of the PBR is a mosaic of grass and shrub savannas, woodland savanna, dry forest, and riparian forest along rivers (Lopes et al., 2020; Fig. 1). The Pendjari River is the only significant watercourse that runs through the reserve (Delvingt et al., 1989). PBR shelters several emblematic and endangered mammal species such as African elephant, topi antelope or korrigum, kob, western hartebeest, African buffalo, waterbuck, hippopotamus, lion, leopard, cheetah, and many other wildlife species listed in the Benin Red List. Currently, managers use early fires in November–December to promote regrowth and limit late fires that are mostly of anthropic origin.

2.2 Data Collection

For the present study, we used MODIS monthly burned area product MCD64A1 v.6.1. The MODIS MCD64A1 fire data are monthly worldwide gridded 500 m products that include per-pixel burned-area and quality data (Giglio et al., 2021). MODIS MCD64A1 detects estimated burning dates and maps the spatial area of monthly fires. The datasets were obtained from the website <https://earthexplorer.usgs.gov/>. We focused our analyses on twenty fire seasons from 2001 to 2021, from October to September.

2.3 Data Analysis

2.3.1 Spatio-temporal analysis of the fire regime To capture the temporal and spatial aspects of fire regimes, we employed a mix of approaches. This methodological approach was based on the work of Smith and Wooster (2005), Archibald et al. (2010a), and Stellmes et al. (2013). In this study, fire regimes in the PBR were described by four indicators: burned area, fire seasonality, fire frequency, and mean fire return interval (MFRI).

The yearly map of burned areas was produced by summarizing the monthly burned area data collected from MCD64A1 products. The pixels in MCD64A1 product with a value between 1 and 366 (Julian days) were sorted into burned area per year and the corresponding dates were noted (Roy et al., 2008). The total area burned (km²) was computed with ArcGIS software v.10.4. We removed all invalid pixels from the dataset (clouds, water, and aerosols) (Archibald et al., 2010a; Stellmes et al., 2013).

To explore burned area variations within and between years, we divided the fire seasons into three parts: early dry season (October–December), late dry season (January–April), and rainy season (May–September) according to the annual pattern of rainfall distribution in the PBR (Houehanou et al., 2017). To assess the dynamics of fire throughout the year, we extracted the mean and standard deviation of the area burned per month for each period.

2.3.2 Fire frequency and MFRI The number of fires that occur in a certain location over time is referred to as fire frequency. The number of times each pixel burned throughout the twenty-year period was calculated by combining monthly burned area layers (Archibald et al., 2010a; Stellmes et al., 2013).

According to Ribeiro (2007), the MFRI is the experienced return time of a fire at a specific location, or the average number of years between two consecutive fires at a specific location, and was calculated using the following formula:

$$\text{MFRI} = \frac{N \times A}{a}$$

where N is the period under study (20 years); A is the total area under study (km²); and a is the total area burned during the period under study (km²) (calculated as the sum of burned areas).

Annual percentage of area burned (APAB) is the average annual percentage of the study area burned. The APAB was calculated using the following formula:

$$\text{APAB} = \frac{a}{N \times A}$$

The MFRI and APAB were calculated for the entire reserve and by land cover type.

2.3.3 Fire Return Interval (FRI) mapping To analyze the spatial distribution of the FRI, we resampled the monthly burned area raster to 30-m pixel size. Then we combined monthly burned area data to produce the burned area map for each year in ArcGIS v.10.4. Annual burned maps corresponding to total area burned were reclassified to produce an image with two grid codes (one for burned pixels and zero for unburned ones). Annual rasters were added to create a composite fire frequency map for the twenty-year period corresponding to the number of times each pixel burned during the period. FRI (i.e., the average number of years between two fire events) was then obtained using the raster calculator tool in ArcGIS v.10.4 with the following formula:

$$\text{FRI} = \frac{N}{\text{raster of fire frequency}}$$

The FRI map had 20 frequency grid codes corresponding to the number of times a fire returned to a particular area during the twenty-year period. For example, a grid code with 1 as FRI frequency means that the area was burned each year while a grid code with 20 indicates areas burned only one time during the study period.

2.4 Statistical Analysis

We tested the correlation between areas burned in early dry season and late dry season during the 20 fire seasons using Pearson correlation test. Fire seasons were grouped into four periods: 2001–2006, 2006–2011, 2011–2016, and 2016–2021. They were considered separately for a 5-year cycle to account for changes in total burned area. We compared the burned areas of early dry fire and late dry fire between the four periods with analysis of variance (ANOVA). We applied logarithmic transformation to the burn area of early dry fire variable to meet ANOVA application conditions of normality and homogeneity of variances. All statistical analyses were performed in R v.4.1.2 (R Development Core Team, 2021), with an alpha value of 0.05 as threshold for significance.

3 Results

3.1 Spatial-temporal distribution of wildfires

Fire season in the PBR extends from October to May with a peak in early dry season (November–December) (Fig. 2 [Figure 2: see original paper]). Very few surfaces were burned in the rainy season, only in May. Of the 20 fire seasons considered for this study, the average surface burned in May was 2.04 km². No surface was burned during the months of June–September over the 20 fire seasons considered.

There was a decrease in the annual total burned areas in the PBR over the two decades of fire seasons under study. However, the burned areas in the PBR increased and decreased over time alternately (Fig. 3 [Figure 3: see original

paper]). It has been observed that when burned areas were low in one year, there was an increase in the following 1 to 3 seasons. The lowest burned area occurred in the season of 2017–2018 in the PBR (2983.00 km² burned area corresponding to 61.59% of the reserve). This was accompanied by a gradual increase in areas burned in the following seasons, with the last two seasons recording the most burned areas over the 20 fire seasons with respectively 4005.00 km² burned (82.69% of the reserve) during 2019–2020, and 4056.00 km² burned (83.74% of the reserve) during 2020–2021.

3.2 Fire seasonality

Fire occurrences in the PBR are seasonal and burned area varies accordingly. In the PBR, on average 62.30% of the reserve burned in the early dry season, while 9.58% burned in the late dry season. The burned areas in early dry season and late dry season during the 20 fire seasons considered have had a sawtooth trend, while those burned in rainy season have had a linear pattern (Fig. 4 [Figure 4: see original paper]). However, by observing the two curves of early and late dry fires, we found an inverse similarity in their appearance. The correlation test carried out between these two variables revealed, as expected, a strong negative correlation ($r = -0.74$, $P < 0.05$) between areas burned early and late in a dry season. Early fires therefore reduce the prevalence of late fires. The last two fire seasons (2019–2020 and 2020–2021) recorded the highest areas burned in the PBR out of the 20 fire seasons studied.

By grouping burned areas into five-year cycles over the last 20 fire seasons, we found a constant downward trend in early dry seasons (Fig. 5 [Figure 5: see original paper]) without significant difference over the four cycles ($P > 0.05$). The early fire cycle of 2001–2006 had the highest average area burned while that of 2016–2021 had the lowest average area burned. Late burned surfaces showed an upward trend with non-significant difference ($P > 0.05$). The fire cycle of 2001–2006 had the lowest average area burned, while that of 2016–2021 had the highest average area burned in late dry seasons.

3.3 Fire frequency and FRI

Total area burned in the PBR during the twenty-year period (2001–2021) was 69,688 km², which is equivalent to more than 14 times the size of the study area. PBR does not burn uniformly. Fire frequency varied from 0 to 24 over the 20 fire seasons considered, indicating that few areas burned more than once during the same season. FRI indicates that fire returned to a particular site every 1.39 years and the APAB in the PBR was 71.94%. During the twenty-year period, 8.21% of the reserve burned every 10–11 months and 11.52% burned annually. Most parts of the reserve burned every one to two years (63.08%), while 8.28% burned every two to four years, 5.82% burned every four to ten years, and 1.89% burned every ten to twenty years (Fig. 6 [Figure 6: see original paper]). Only 1.29% of the whole area did not burn during the study period. These unburned

areas represent bare ground, water areas along the Pendjari River, and human occupation areas.

Fire frequency varied differently depending on land cover type (Table 1). Spatial distribution of burned areas over the 20 fire seasons according to land cover types showed that MFRI was low in grasslands, shrub savanna, tree savanna, woodland savanna, and rock vegetation (MFRI < 2.00 years). The highest MFRI, 6.38 years, was observed in crop areas with low contribution to burned area (APAB = 0.56%). APAB of shrub savanna, grasslands, and tree savanna had the higher values, being 41.04%, 14.58%, and 11.56%, respectively, which showed high contribution to burned area. The three land cover types that had the lowest contribution to burned area were forest, temporary wetland, and crop with APAB < 1.00%.

Table 1 Fire frequency by land cover type in the Pendjari Biosphere Reserve

Type of land cover	Area (km ²)	MFRI (years)	APAB (%)
Grasslands		1.19	14.58
Shrub savanna		1.25	41.04
Tree savanna		1.43	11.56
Woodland savanna		1.53	8.84
Forest		2.06	0.92
Temporary wetland		2.35	0.64
Rock vegetation		1.89	1.96

Note: Bare ground (158 km² and 3.3%) and water body (3.22 km² and 0.06%) were not included. MFRI, mean fire return interval; APAB, annual percentage of area burned.

4 Discussion

Using remote sensing data, we have gained a better understanding of the fire regime in the PBR. Fires occur throughout the year in the PBR, but there is high spatial and temporal variability. Fire season in the PBR extends from October to May with a peak in early dry season (November–December). Fire occurrence and climate conditions, especially temperature and precipitation, are closely related (Machado et al., 2014; Silva et al., 2019). Fires depend more on climate conditions when it is hot in the absence of rain and high vapor pressure deficit of the atmosphere (Machado et al., 2014), and managers set fires at the beginning of the dry season before the period of peak conditions. According to Takacs et al. (2021), who studied the factors that shape fire size and spread in the PBR, fires spread faster from November to February (early to mid-dry season) compared with October and the end of the dry season (March/April).

Our study also shows a strong negative correlation between areas burned early and late in the dry season. The latter can be explained by the fact that the first

fires (November–December) extremely reduce fuel availability in the landscape and thus the predisposition of the reserve to burn in the late dry season. The landscape is in a drying phase at the start of the fire season, with a reduction in grass and soil moisture (Mathieu et al., 2019). Although early season fires are predicted to be less intense and perhaps less complete than those of late season (Govender et al., 2006), grass removal by early season fires can have several effects, including removal of grass scatter, reduced grass moisture and fire-induced soil moisture changes (Menges et al., 2004), all of which can help prevent late and catastrophic fires (Namukonde et al., 2017).

In the PBR, we observed that when burned areas are low for one year, fire occurrence increases during the following 1–3 seasons, displaying a cyclical trend. Studies by Ullah et al. (2013) in China show that when fire occurrence is low in the first two years, it becomes high in the next three years, showing a five-year cycle. The cyclical trend of extreme fires and low fires observed can be explained by the fact that after a catastrophic fire having decimated the biomass in a given year, the ecosystem requires one to two years to reconstitute sufficient vegetation cover for a second occurrence of intense fires (Gueguim et al., 2018).

There is a constant downward trend of fire in the early dry season and an increase in late dry season over the four cycles of five years. The result suggests that early fires are used less and less, which favors the occurrence of late fires. Indeed, the current management of the PBR from 2016 to present tends to limit the use of management fires. Thus, the extent of fire in late dry season that occurred during 2016–2021, with the largest area burned during 2020–2021 although climate conditions were similar to previous seasons, was due to the attempt of reserve management to suppress fires and the consequent increase of dead and dry biomass, making it susceptible to late fires. Grass biomass is mainly regulated by soil fertility and rainfall, but it is also affected by time since grass biomass accumulates from one year to the next in the absence of fire (Govender et al., 2006).

The entire PBR does not burn uniformly. The MFRI indicates that fire returned to a particular site every 1.39 years and the APAB in the PBR is 71.94%. During the twenty-year period, most area in the reserve burned every one to two years (63.08%) and only 1.29% of the whole area did not burn during the study period. This result is similar to values observed in Burkina Faso protected areas, a savanna region in West Africa (Devineau et al., 2010), where yearly or biennial fires are most predominant (47.40%). However, the MFRI (1.39 years; APAB=71.94%) in the PBR is lower than those obtained in West Arnhem Land, a savanna region of northern Australia, where MFRI ranged from 2.70 to 2.80 years (APAB=36.00%–37.00%) (Oliveira et al., 2013), as well as that obtained in Jalapao State Park in Brazil, where MFRI is 3.00 years (APAB=33.00%) (Pereira Júnior et al., 2014) and in Niassa National Reserve, northern Mozambique, where MFRI is 3.29 years (Ribeiro et al., 2017). All of these reserves have been using fire as a land management tool for decades. The West African savannas are found in an arid/semi-arid area where temperature

is very high in the dry season with almost no rain and the quantity of fuel available is also greater, which results in the low return period. However, having found that the reserve did not burn uniformly, we suggest that MFRI must be analyzed in conjunction with its spatial distribution across the landscape for good management decisions.

Fire frequency varied differently depending on land cover type. MFRI was low in grasslands, shrub savanna, tree savanna, woodland savanna, and rock vegetation (MFRI < 2.00 years), and MFRI > 2.00 years in forest, temporary wetland, and crop areas with low contribution to burned area. The highest MFRI was observed in crop areas surrounding the PBR. The southwestern part in the controlled occupation zone registered the highest MFRI, 6.38 years with low contribution to burned area (APAB = 0.56%). Farms, cleared areas, and generally landscapes with discontinuities decrease fire spread and burned area size (Devineau, 1986; Clerici, 2006; Dolidon, 2007). Cultivation areas are associated with strong human presence, which justifies the high MFRI and therefore low contribution to burned areas. In follow-up studies, Archibald et al. (2010b) and Cangela (2014) found that human density was associated with reduced fire frequency. Shrub savanna and grasslands had the highest APAB (41.04% and 14.58%, respectively) coupled with low MFRI (1.19 and 1.25 years, respectively). This is due to high accumulation of fuel in these habitats, which are burned during the fire season. Fire incidence was low in forest and temporary wetland because they are closed forest formations in humid habitats along rivers, and fuel remains very moist throughout the year. In contrast, tree savanna and woodland savanna that are open vegetation with very dry fuel biomass are affected by fire incidents during the fire season and therefore reduce MFRI to less than 2.00 years. According to Frost (1996), Chidumayo (1997), and Ribeiro (2007), an FRI range between 2.00 and 4.00 years is needed to allow woody vegetation to grow in areas above the threshold where they are killed by fire. As tree species in woodland savanna have developed fire-resistant mechanisms, such as thick and/or corky bark, rapid early growth, and vigorous regrowth (Nefabas and Gambiza, 2007; Lawes et al., 2011), savanna fires rarely affect large trees unless they have been previously damaged by animals (Shannon et al., 2011; N' Dri et al., 2014). However, late dry fires with MFRI of less than 2.00 years in woodland savanna would eliminate forest regrowth and be detrimental to the sustainability of woody vegetation.

To preserve the integrity of the PBR, it is critical to maintain a fire regime that supports tree-grass interactions and allows for a balance between tree cover and diversity, as well as grass supply available to herbivores. In this context, we suggest applying late dry fires two to three years after using early dry fires in shrub savannas to limit the expansion of shrubs and bushes and thus retain vegetation integrity. We also suggest using early fire in tree savannas and woodland savannas where MFRI is less than 2.00 years to lower grass height and hence fuel supply in the environment. This enables trees to recover faster by releasing more nutrients and reducing grass competition (Govender et al., 2006). In locations where fire frequency is sufficient to enable tree development (every

three to four years), we recommend a laissez-faire approach (no interference with the present fire regime). This management technique has been successfully applied in several other protected areas, including Kruger National Park in South Africa (Govender et al., 2006) and a forest management area in Kilwa, Tanzania (Mariki, 2016). These fire-prone landscape management practices can thus be applied elsewhere, but first the fire regimes in the landscape must be assessed. There is evidence that wildlife distribution in fire-prone landscapes is related to fire events (Reich et al., 2001; Eby et al., 2014). It is therefore important to maintain good use of fire for management of protected areas that will consider the holistic approach of conserving the sustainability of vegetation and wildlife.

5 Conclusions

This study shows that remote sensing is a useful tool that can help effectively monitor fire regime and therefore better manage fire in fire-prone landscapes like the PBR. Fire season in the PBR extends from October to May with a peak in early dry season (November–December). Fire returned to a particular site every 1.39 years and the APAB in the PBR was 71.94%. MFRI was low in grasslands, shrub savanna, tree savanna, woodland savanna, and rock vegetation ($MFRI < 2.00$ years), while $MFRI > 2.00$ years in forest, temporary wetland, and crop areas. Continued fire monitoring as well as determining how wildlife select habitats in fire-prone landscapes will help better design fire management plans in wildlife reserves for the sustainable conservation of these animals that are intrinsically linked to landscape variations.

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