Dahan et al. Fire Ecology (2023) 19:42
https://doi.org/10.1186/s42408-023-00198-z

Fire Ecology

ORIGINAL RESEARCH

Open Access

Contribution of remote sensing to wildfire trend and dynamic analysis in two of Ghana's ecological zones: Guinea-savanna and Forest-savanna mosaic

Kueshi Sémanou Dahan[1,2*], Raymond Abudu Kasei[2,3] and Rikiatu Husseini[4]

Abstract

Background Two of Ghana's ecological zones—Guinea-savanna zone (GSZ) and Forest-savanna mosaic zone (FSZ)—are practically homologous in terms of structure and floristic composition, with some differences. The various sub-ecosystems that make up these areas are being depleted and losing their natural values due to various threats. There is little understanding about the fire trends in these areas due to a lack of data and poor accessibility to existing fire statistics. This study aimed to contribute to the understanding of the trends of area burned and active fire in the Guinea-savanna and Forest-savanna mosaic zones in order to inform policy-makers about sustainable management options. We used the Moderate Resolution Imaging Spectroradiometer (MODIS) daily active fire (MDC14ML) and burned-area (MCD64A1) products to characterize the fire regime in terms of seasonality, intensity, density, burned area, frequency, and trends during the study period of 2001 to 2021.

Results This study indicated that fire activity started in October and peaked in December (GSZ) and January (FSZ). The mean proportion burned was approximately 39.95% (burned area of 2659.31 km^2; FSZ) and 60.05% (burned area of 3996.63 km^2: GSZ), while the frequency was approximately 42.87% (1759.95 of active fires; FSZ) and 57.13% (2345.26 of active fires: GSZ). In 2018, GSZ recorded the largest burned area (19811.2 km^2, which represents an average of 825.5 km^2 of the total area burned from 2001 to 2021) with 4719 active points detected. FSZ recorded its greatest burned area in 2015 (8727.4 km^2; which represents an average of 363.6 km^2 of the total area burned from 2001 to 2021) with 5587 active points recorded. In addition, it was found that specific times of the day (1000 h to 1420 h) recorded the majority of burned areas. In overview, between 2001 and 2021, burned areas increased by an average of 1.4 km^2 (FSZ) and 4.6 km^2 (GSZ), and the number of active fires increased by an average of 4.7 (FSZ) and 4.4 (GSZ) active fires per km^2.

Conclusions In conclusion, burned areas and active fires are increasing in both ecological zones. This study demonstrated the relevance of remote sensing to describe spatial and temporal patterns of fire occurrence in Ghana and highlighted the need for fire control and fuel management by the policies and institutions (e.g., Ghana National Fire and Rescue Service) in these important and vulnerable zones (GSZ and FSZ). This is especially true in the Forest-savanna mosaic zone, which is increasingly affected by the disasters of wildfires and records more active fires than GSZ, indicating that this zone is becoming more and more vulnerable. Therefore, rigorous continuous monitoring is essential, and collaboration between organizations fighting for the conservation of natural resources in the field is strongly recommended.

*Correspondence:
Kueshi Sémanou Dahan
dkueshi09@gmail.com
Full list of author information is available at the end of the article

Keywords Forest-savanna mosaic zone, Ghana, Guinea-savanna zone, MODIS active fire, MODIS burned area, Remote sensing

Resumen

Antecedentes Dos regiones ecológicas de Ghana—la Zona de la Sabana de Guinea (GSZ) y el Mosaico de Bosque Sabana (FSZ)—son prácticamente homólogas en términos de estructura y composición florística, aunque con algunas diferencias. Los distintos sub-ecosistemas que constituyen esas áreas están siendo devastados y perdiendo sus valores naturales debido a varias amenazas. Existe muy poco conocimiento sobre las tendencias de los incendios debido a la falta de datos y a una pobre accesibilidad a las estadísticas existentes sobre fuegos. Este estudio estuvo dirigido a contribuir al conocimeinto de las tendencias de áreas quemadas y fuegos activos tanto en la Zona de la Sabana de Guinea (GSZ) como en el Mosaico de Bosque-Sabana (FSZ)—de manera de informar a los gestores y tomadores de decisiones sobre opciones de manejo sustentable. Usamos los productos del sensor radiométrico de imágenes de resolución moderada (MODIS), de los fuegos diarios activos (MDC14ML) y del área quemada (MCD64A1), para caracterizar el régimen de fuegos en términos de estacionalidad, intensidad, densidad, área quemada, frecuencia, y tendencias durante el período de estudio ubicado entre 2001 y 2021.

Resultados Este estudio indicó que la actividad de los fuegos comenzó en octubre y llegó a un pico en diciembre (en GSZ) y en enero (en FSZ). La proporción media del área quemada fue de aproximadamente 39,95% (área quemada de 2.659,31 km^2, en FSZ) y 60,05% (área quemada de 3.996,63 km^2, en GSZ), mientras que la frecuencia fue aproximadamente del 42.87% o 1.759,95 fuegos activos, en FSZ), y 57,13% o 2.345,26 fuegos activos, en GSZ. En el año 2018, GSZ registró la mayor área quemada (19.811,2 km^2, o un promedio de 825,5 km^2), con 4.719 puntos activos detectados, mientras que FSZ registró su mayor área quemada en 2015 (8.727,4 km^2), con 5.587 puntos activos registrados, lo que representa un promedio de 363,6 km2 de área quemada del total del área quemada desde 2001 a 2021. Adicionalmente, se encontró que a horas específicas del día (de 10:00 a 14:20 h) se registró la mayor cantidad de superficie quemada.

Conclusiones En conclusión, la tendencia muestra un decrecimiento en la superficie quemada, y un incremento en el número de fuegos. Este estudio demostró la relevancia de los sensores remotos para describir los patrones espaciales y temporales en la ocurrencia de incendios en Ghana, y resaltan la necesidad de control de incendios y manejo de los combustibles por parte de las políticas e instituciones (e. g. Servicio Nacional de Fuego y Rescate de Ghana) en estas zonas importantes y vulnerables (GSZ y FSZ), especialmente en el mosaico bosque-sabana (FSZ), el cual está siendo incrementalmente más afectado por desastres de incendios y registra fuegos más y más activos que en la zona GSZ. Por esas razones, es fuertemente recomendable y esencial, un monitoreo continuo, riguroso y colaborativo entre organizaciones que luchan por la conservación de los recursos naturales.

Introduction

Wildfire is an integral and inevitable ecological disturbance process in forest ecosystems worldwide (Bowman et al. 2020). However, fire is also a pervasive disturbance for many terrestrial ecosystems (Bowman et al. 2009; Pausas and Keeley 2009; Wysong et al. 2022) and an important landscape management tool used by humans for millennia (Pyne 1997; Bowman et al. 2011; Huffman 2013). Both natural and anthropogenic burning affect ecosystem structure and composition worldwide (McLauchlan et al. 2020). The controlled application of fire, such as through prescribed burning, is commonly used to reduce fuel and enhance fire breaks to protect specific tracts of land and limit the spread of wildfire (Wysong et al. 2022). While there is considerable debate over the efficacy of prescribed burning in different biomes, its application can reduce the impacts of fire in some contexts (Fernandes and Botelho 2003; Penman et al. 2011). In modern times, large wildfires are increasingly affecting terrestrial ecosystems and threatening human health, safety, and livelihoods, posing immense challenges for land managers (Krawchuk et al. 2009; Boer et al. 2020). In Australia, for example, thousands of fires between June 2019 and March 2020 burned more than 18.6 million hectares, causing 34 fatalities and the loss of 3500 homes (Munawar et al. 2021).

With respect to African savanna ecosystems, fire is an important ecological component (van Langevelde et al. 2003). In some areas, landscape composition appears to be a less important determinant of the area burned by fires (Podur and Martell 2009), although this may vary with location (Cumming 2001; Heyerdahl et al. 2001; Bergeron et al. 2004). Researchers have debated the relative influences of weather, climate, and landscape on fire

(Agee 1997). In other regions, such as the Mediterranean, fires have differentially burned certain land-use and land-cover (LULC) types (Moreira et al. 2001, 2009; Nunes et al. 2005; Bajocco and Ricotta 2008), suggesting that landscape is a more critical factor in these regions. In the Sudanian savanna-woodland alone, an area stretching from Senegal in the west to the Ethiopian highlands in the east (between 6° and 13° N; Menaut et al. 1995), between 25 and 50% burns annually (Delmas et al. 1991).

Although studies have quantified degrees of burning by LULC type or other landscape variables for many world regions (Cumming 2001; Vázquez and Moreno 2001; Mermoz et al. 2005), many have simply provided averages of the area burned for the categories of a given variable, or they have performed statistical analyses that did not fully account for the nature of burned-area data. Fires are not normally distributed, and they vary in size by several orders of magnitude (Moreno et al. 1998; Keeley et al. 1999; Boer et al. 2008). Also, burned area sample units below the level of a single fire are not spatially independent, owing to the contiguous spread of fire through the landscape. Furthermore, fires are temporally and spatially correlated (Chou et al. 1990).

The dynamic nature of the landscape deserves particular attention. Therefore, spatial and temporal information on savanna fires and controlled burning in savannas and vulnerable ecosystems is important for research and management within disciplines such as fire ecology (Gibb et al. 2022), atmospheric chemistry (Hao et al. 1990; Menaut et al. 1995), soil studies (Butler et al. 2019), and forestry (Liu 2015; Tian et al. 2017; Hopkins et al. 2020). Fire hazard on the landscape varies over time, owing to, among other factors, post-fire succession and subsequent fuel accumulation patterns in burned areas (Wysong et al. 2022). These spatially heterogeneous processes (Turner et al. 1997) change landscape composition and the spatial relationships between various areas. Given the relevance of these changes in highly humanized landscapes, as in the Guinea-savanna or Forest-savanna mosaic regions, the assessment of fire risk necessitates an understanding of the spatial and temporal changes in LULC characteristics as fires continue to occur.

In Ghana, frequent wildfires generally negatively affect social, cultural, and environmental services and economic values, especially in the most vulnerable northern and transitional regions. Every year, an average of 684 000 ± 4000 km^2 (25 to 32%) and 372 600 ± 2600 km^2 (46 to 60%) of land are burned in all of Ghana and the northern region of Ghana, respectively. The wildfires of the northern region of Ghana account for 53 to 56% of all annual fires, despite accounting for only 29% of the country's total dry land area (Kugbe et al. 2012). Such fires threaten the safety of remote communities and outstations and incur high emergency response costs. Nowadays, large wildfires are increasingly affecting terrestrial ecosystems and threatening human health, safety, and livelihoods, posing immense challenges for the land tourism industry that relies on access to natural environments and outdoor activities (Axford and Legge 2008; Blanch 2008; Russell-Smith and Whitehead 2015). For instance, wildfires in tropical savannas are a significant contributor to global annual greenhouse gas emissions (Russell-Smith et al. 2009).

Our research aimed to contribute to the understanding of the burned area and active fire trends through their spatial and temporal dynamics in Ghana's two ecological zones (Guinea-savanna zone, GSZ; and Forest-savanna mosaic zone, FSZ) that are most vulnerable to climate change. This objective was based on the assumption that anthropogenic fire activities are becoming increasingly important in the FSZ as well as in the GZS. This assumption is also supported by the climatic realities of these different zones. The GSZ has a monomodal climate characterized by a wet, rainy season (June to October), which stimulates the abundant growth of grasses that dry up during the dry season (November to June). However, the FSZ has a bimodal climate with wet (April to July and September to November) and dry (July to August and October to March) periods (Owusu and Waylen 2009; Stanturf et al. 2011; Braimah et al. 2022). These climatic differences, in one way or another, affect the behavior of vegetation fires in these regions.

Policy reorientation in forest and natural resource management in Ghana is needed. However, contemporary research data needed to inform such change are either insufficient or even completely lacking. To fill this knowledge gap, 21 years (2001 to 2021) of burned-area and active-fire data in the two ecological zones (GSZ and FSZ) were studied. Indeed, the issue of climate vulnerability led us to select districts such as West Mamprusi and West Gonja in the Guinea-savanna ecological zone, and Sene and Afram Plain in the Forest-savanna mosaic ecological zone to better circumscribe our study. The results of this study could be used by management to help diminish future increases in fire risk due to climate change (Christensen et al. 2007) and socioeconomic change (Syphard et al. 2008). Furthermore, local impacts on global warming could be lessened.

The questions that this study sought answers to were as follows: How are fire events evolving in the GSZ and FZS zones? What is their magnitude? And specifically, is the FSZ becoming increasingly exposed to wildfires? Data pertinent to these questions have been analyzed in this study through a remote sensing approach supported by statistical analysis to assess their trends and to evaluate their seasonal and annual activities.

Methods

Study sites

Our areas of focus in the Guinea-savanna ecological zone (GSZ) of Ghana were West Gonja and West Mamprusi, located between latitude 10.45028° and 9.53361° N and longitude 0.46666° and 2.30000° W, with an area of 13,880.41 km^2 (Fig. 1). The Guinea-savanna ecological zone is composed of extensive wooded savannas and open Guinean savannas, which are characterized by natural wooded savannas with cultivated lands (CILSS 2016). According to Menczer and Quaye (2006), the Guinea-savanna zone consists of tall grasses growing between widely spaced trees. There are no commercial tree species. Plantations of *Tectona grandis* L.f. (teak) are growing well (MOFA 2015); however, they are not exploited us commercial trees in that zone. There are two main tree species—*Faidherbia albida* (Delile) A.Chev. (syn. *Acacia albida* Delile; apple-ring acacia) and *Adansonia digitata* L. (baobab). *Parkia biglobosa* (Jacq.) R.Br. ex G.Don (dawadawa), *Adansonia digitata* L. (baobab), *Vitellaria paradoxa* C.F.Gaertn. (shea), and *Mangifera indica* L. (mango) are also commonly found trees, in terms of dominance and abundance (MOFA 2015).

In the Forest-savanna mosaic ecological zone (FSZ), the districts we focused on for this study, Sene and Afram Plain, are located between latitude 6.58361° and 8.15028° N and longitude 1.6669° and 0.51694° E, with an area of 13 880.41 km^2. Structured into several sub-zones, the Forest-savanna mosaic zone is located in central Ghana and composed of the Main Transitional Zone, Eastern Transitional Zone, and Central Transitional Zone. It has an intermediate climate that has two rainy seasons and transitional Forest-savanna vegetation (Fig. 1). The significant commercial tree species include *Milicia excelsa* (Welw.) C.C.Berg (odum), *Antiaris africana* Engl. (kyenkyen or chenchen), and *Triplochiton scleroxylon* K.Schum. (wawa). The area is also dominated by some indigenous species (Nindel 2017), including *Celtis mildbraedii* Engl. (esa), *Entandrophragma angolense* (Welw.) Panshin (edinam), *Pycnanthus angolensis* (Welw.) Warb. (otie), *Piptadeniastrum africanum* (Hook.f.) Brenan (dahoma), *Amphimas pterocarpoides* Pierre ex Harms (yaya), *Chrysophyllum albidum* G.Don (akasaa), and *Daniellia ogea* (Harms) Rolfe ex Holland (hyedua). The landscape can be described as a mosaic of diverse elements including

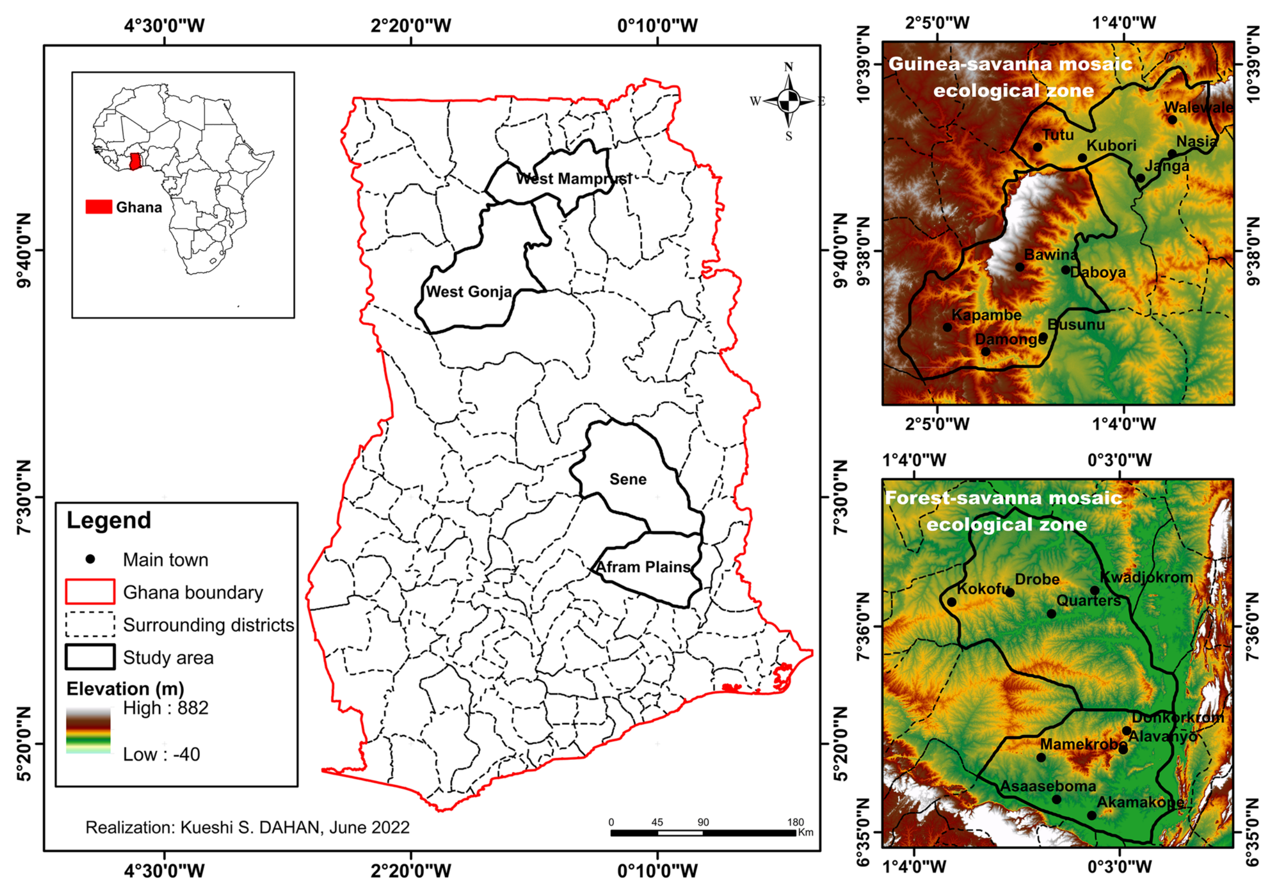

Fig. 1 Location of the study areas used during research to characterize the fire regime of two ecological zones, Guinea-savanna and Forest-savanna mosaic, in Ghana using a remote sensing approach, during the study period 2001 to 2021

forest types, human settlements, hydrological systems, and agro-ecological niches (Ayivor et al. 2015).

Methods of imagery analysis, fire mapping, and trend assessment

The materials and data common to the study objectives that were used were as follows. The digital geographic contour layers (road network, localities, etc.) were downloaded in a shapefile extension from http://diva-gis.org/datadown and geoprocessed in ArcGIS Desktop version 10.5 (ESRI, Redlands, California, USA) and MS Excel 2013 (Microsoft, Redmond, Washington, USA), and the statistical software programs Statistica (StatSoft, Paris, France), Khronostat 1.01 (IRD, Montpellier, France), and R (RStudio PBC, Boston, Massachusetts, USA) were used to perform, respectively, Hierarchical Clustering on Principal Components (HCPC; Zheng et al. 2020) analysis, Pettitt test (Pettitt 1979), and Mann-Kendall test (Kendall 1975). Field equipment used included a Garmin handheld GPS unit (GPSMAP 64csx; Garmin Ltd., Olathe, Kansas, USA) to record the coordinates (X; Y) of the different fire density level checkpoints.

Acquisition of fires data and mapping the spatio-temporal dynamics of fires

Different sensors are available for monitoring active fires and burned areas. For our study, the monthly time series of medium spatial resolution remote sensing images (2001 to 2021) operated by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor was used. These were chosen because of their availability, ease of access to the necessary data, the daily coverage of large areas, and their spatial resolution of 250 m (Jacquin 2010).

The MODIS product used for burned area assessment was from collection 6.1 (Giglio et al. 2020). The images of burned area (MCD64A1) and active fire (MCD14ML) were downloaded from platforms provided by NASA (National Aeronautics and Space Administration) at https://ladsweb.modaps.eosdis.nasa.gov/search/order/ and https://firms.modaps.eosdis.nasa.gov/download/, respectively. They have a spatial resolution of 250 m and a daily temporal resolution summarized in monthly data (Giglio et al. 2020). MCD64A1 explores and locates abrupt change in surface reflectance following the method described by Roy et al. (2005). In this study, over a 20-year study period (2001 to 2021), 756 images (in Hierarchical Data Format; HDF) were acquired at a rate of three images per month for burned area, which were converted into shapefile format for active fires.

Analysis of active fires

Active fire points were ranked on a reliability scale of 1 to 100, 100 being the most reliable. Confidence levels were based on quantitative adjustments to the algorithm in the detection process. Three classes of fire pixels (low confidence, nominal confidence, and high confidence; Table 1) are provided in the fire masks of the MODIS Level 2 and Level 3 fire products. Because it may be useful to exclude false-positive fire occurrences (Valea 2005; Giglio et al. 2020), users may wish to consider only nominal and high-confidence fire pixels and treat low-confidence fire pixels as clear non-fire land pixels (Giglio et al. 2020). In our work, fire points with a reliability of more than 30% were considered (Caillault et al. 2010) to establish a base containing only proven fire points (Fig. 2).

Calculation of fire density and frequency

The density (D) of fire indicates the number of fires per unit area. It provides information on the spatial distribution of fire within the area considered. Densities obtained from the map were checked in the field to ensure that the results from the processed image corresponded to the reality on the ground. A total of 64 points for low and non-burned, and 106 points for high burned, as determined by the kriging spatialization technique (Childs 2004), were checked. The formula of Valea (2005) was used:

$$D = \frac{n_{\mathrm{i}}}{s_{\mathrm{i}}} \tag{1}$$

where n_{i} is the number of fire points in the administrative boundary; s_{i} is the area of the administrative unit (in km^2). The density of the number of fires was calculated using the kriging spatialization technique, with the adoption of the following density classification levels (per km^2): very low density (<2.33 fires km^{-2}), low density (2.33 to 5.768 fires km^{-2}), little density (≥5.768 to 6.408 fires km^{-2}), medium density (≥6.408 to 7.765 fires km^{-2}), and high density (>7.765 fires km^{-2}).

The frequency (F) of fire shows the percentage of fire in any one area. It was calculated using the formula by Valea (2005):

Table 1 Ranges assigned to the three confidence (C) classes of fire pixels (low confidence, nominal confidence, and high confidence; according to Giglio et al. 2020). These were provided in the fire masks of the MODIS Level 2 and Level 3 fire products that were used during research from 2001 to 2021 to characterize the fire regime of two ecological zones, Guinea-savanna and Forest-savanna mosaic, in Ghana, using a remote sensing approach

Range	Confidence class
0% ≤ C <30%	Low
30% ≤ C <80%	Nominal
80% ≤ C <100%	High

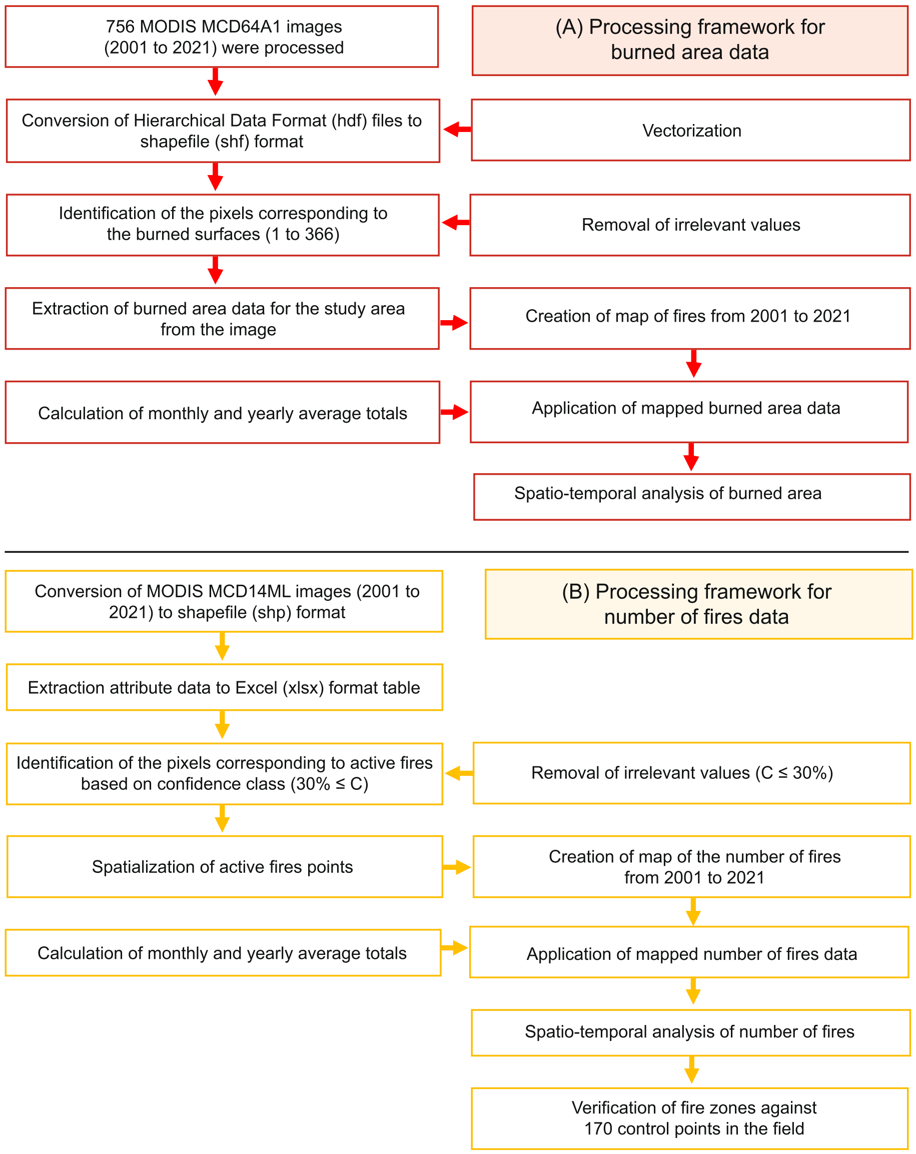

Fig. 2 Methodological framework for processing (**A**) burned areas image data and (**B**) number of fires data recorded during research to characterize the fire regime of two ecological zones, Guinea-savanna and Forest-savanna mosaic, in Ghana, using a remote sensing approach, during the study period 2001 to 2021

$$F = \left(\frac{n_i}{N_i}\right) \times 100 \quad (2)$$

where n_i equals the number of fire points in the study area, and N_i is the total number of fires.

Burned areas, fire occurrence, and intensity assessment

The MODIS burn date covering a period of one month is presented in a series of elementary images described by six sets of information (Boschetti et al. 2009). Only one of the six sets was of interest for our research: the set with values from 1 to 366, which correspond to the approximate days of fire (with respect to the Gregorian calendar). Therefore, only pixels with relevant values from 1 to 366 (pixels with high probability of containing fire events per month), were considered. The calculation of burned area was been done per year and per month, according to each study area, after polygonization.

Fire frequency (occurrence) was obtained from the combination of the annual charts of the burned area and then characterized according to Oliveras et al. (2014), who defined frequency as the burn frequency and fire return interval, which is the number of times (in percentage) that a fire recurred in the same spot during the whole study period. Thus, the following classification was established: <22.4 ha = small burned area; ≥22.4 ha and <100 ha = medium burned area; and >100 ha = large burned area.

Statistical analysis of fire data

To highlight the differences between months and years in terms of those most and least affected by fire, or which registered the most or least number of active fires, a principal component analysis and a hierarchical classification analysis were performed (Gordon 1994; Zheng et al. 2020). For the trend evaluation, the Mann-Kendall test was used to analyze the trend in our time series. This non-parametric trend test was the outcome of a refinement of the test initially developed by Mann (1945) and then adopted by Kendall (1975). After the Mann-Kendall trend test, the Pettitt test was used to help us analyze break-up times as the trend was not monotonic.

Mann-Kendall test and inter-annual anomalies

The Mann–Kendall test statistic (S), is a nonparametric method for trend analysis that has been widely applied to regional climate studies (Mann 1945; Kendall 1975). The Mann-Kendall test was used to detect the existence of a single overall trend within a series. The Mann-Kendall test, which is based on Kendall's *t*-rank correlation statistic, is used to show the degree of significance of the trend and to determine the direction of the trend in the time series. It simply gives information on the course and a measure of the significance of observed trends of climatic parameters (Siraj et al. 2013). Thus, the trend analyses were performed using this test. The S-statistic is defined by:

$$S = \sum_{j-1}^{n-1} \sum_{i+1}^{n} sign(x_i - x_j) \tag{3}$$

where x_i was the data value at time i, n is the length of the dataset, and $sign(x_i - x_j)$ is the sign function, which is computed as follows:

$$sign(x_i - x_j)\begin{cases} 1\ if\ (x_i - x_j) > 0 \\ 0\ if\ (x_i - x_j) = 0 \\ -1\ if\ (x_i - x_j) < 0 \end{cases} \tag{4}$$

For $n > 10$, the test statistic Z approximately follows a standard normal distribution as in the following equation:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}\ if\ S > 0 \\ 0\ if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}\ if\ S < 0 \end{cases} \tag{5}$$

where $Var(S)$ is the variance of statistic S. Thus, a positive Z value indicates an increasing trend, whereas a negative value indicates that the trend is decreasing.

In addition, to better identify the increase or decrease in burned areas as well as active fires, the intra-annual anomalies (An) were calculated as follows:

$$An = \frac{X_t - X\text{mean}}{\delta} \tag{6}$$

where X_t is the annual mean observation values during time t (year); X_{mean} is the long-term mean of the series considered throughout the observation period (2001 to 2021), and δ is the standard deviation of the time series considered throughout the observation (2001 to 2021).

Pettitt test

The Mann-Whitney-Pettitt test is derived from the Mann-Whitney test, modified by Pettitt (Pettitt 1979). This test is non-parametric and is based on the fact that the absence of a break in a series means that the hypothesis is null (H_0) and the presence of a break constitutes the alternative hypothesis (H_1). It thus makes it possible to identify a change in the behavior of the data series by comparing two means. A break is defined as a change in the probability law of the random variables whose successive realizations define the time series studied (Servat et al. 1998). The implementation of the test assumes that, for any time t between 1 and N, the time series (X_i), from $i = 1$ to t and from $t + 1$ to N, belong to the same population. The test variable is the maximum absolute value of the variable $U_{t,N}$. In case the null hypothesis is rejected, an estimate of the break date is given by the time t defining the maximum in the absolute value of the variable $U_{t,N}$:

$$U_{t,N} = \sum_{i=1}^{t} \sum_{i=t+1}^{N} D_{ij} \tag{7}$$

with:

$$D_{ij} = sign(x_i - x_j)\begin{cases} 1\ if\ (x_i - x_j) > 0 \\ 0\ if\ (x_i - x_j) = 0 \\ -1\ if\ (x_i - x_j) < 0 \end{cases} \tag{8}$$

To test H_0, we used the variable K_N, the absolute value of the variable $U_{t,N}$:

$$K_N = max_1 \leq t < T\left|U_{t,N}\right| \tag{9}$$

Results

Seasonal evolution of fires

The seasonality of fires was determined for the area burned and the number of active points in each month over the observation period from 2001 to 2021. The seasonal distribution of burned areas showed that wildfires

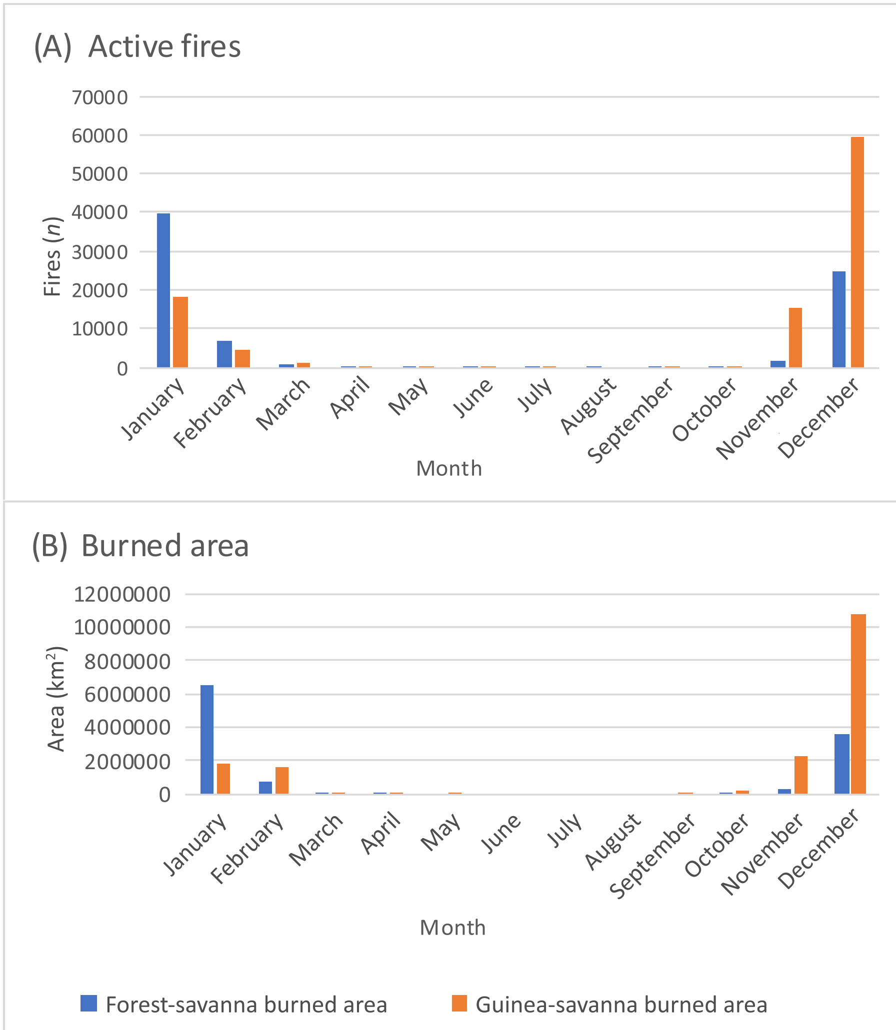

Fig. 3 Monthly averages for (**A**) number of fires and (**B**) area burned per ecological zone (Forest-savanna mosaic and Guinea-savanna ecological zones) recorded from 2001 to 2021 during research to characterize the fire regime of the two zones in Ghana using a remote sensing approach

persisted during a large part of the year in both ecological zones (Fig. 3). There was great variation in the area burned monthly. However, the fire season in the two ecological zones differed slightly as they do not have the same climate types (monomodal in the Guinea-savanna zone and bimodal in the Forest-savanna zone). The months of December and January were the most fire prone and fire ravaged in the Guinean-savanna zone, with a stronger presence in December, positioning it as the month of intense fire activity. The Forest-savanna zone recorded more fire in December and January, with more events in January. Seasonality is thus characterized by a start of the fire season in November in both zones, which continues during the dry period, with a progressive increase in December and January. It is more pronounced in January with 64.857 km^2 burned and 39728 fires detected over the whole study period (21 years) in the Forest-savanna zone; whereas, in the Guinea-savanna zone, it is more pronounced in December (107.539 km^2 burned; 59288 fires detected). Fire occurrence declines from April onwards in terms of surface area burned in these different ecological zones (decreasing by 7.6 km^2 for GSZ and by 69.3 km^2 for FSZ), and becomes almost non-existent in May, June, July, August, and September.

Annual evolution of fires

Fire activity and spread were very significant over the study period, with significant changes in the area burned each year (Fig. 4). In general, the area burned and the

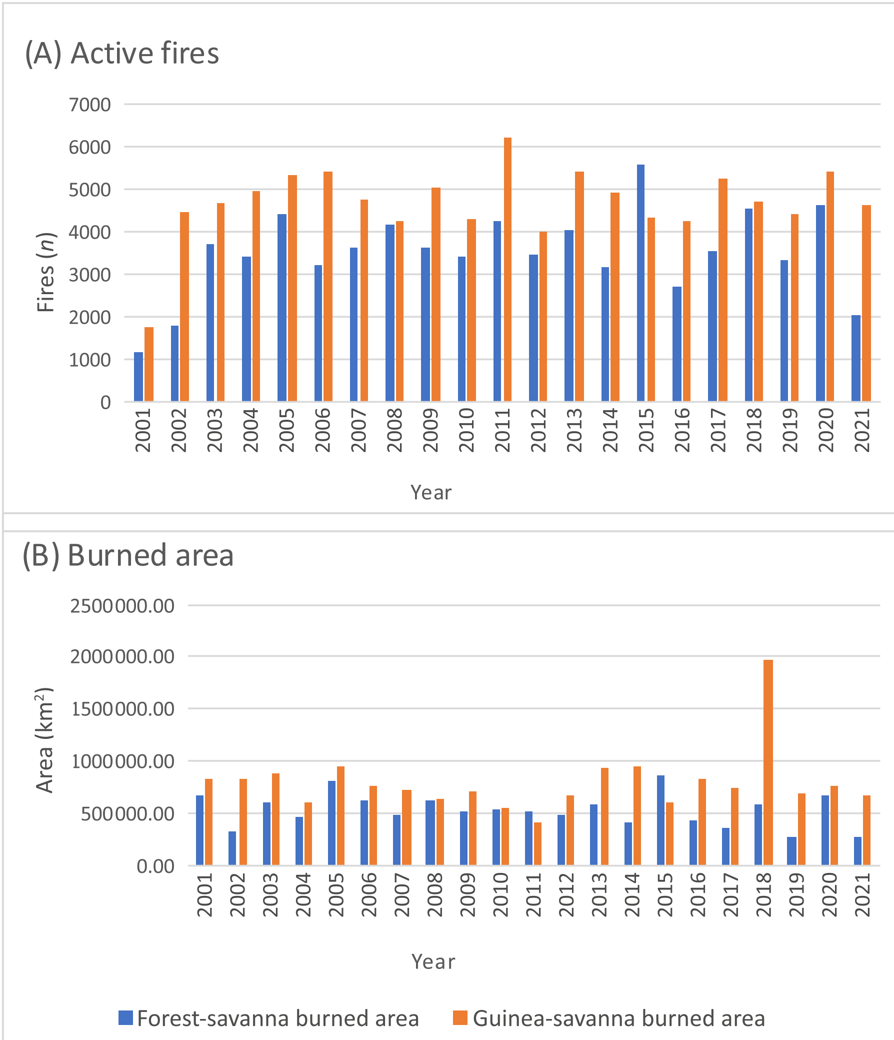

Fig. 4 Yearly averages for (**A**) number of fires and (**B**) area burned per ecological zone (Forest-savanna mosaic and Guinea-savanna ecological zones) recorded from 2001 to 2021 during research to characterize the fire regime of the two zones in Ghana using a remote sensing approach

number of fires per year did not follow a defined trend in the two ecological zones considered. The years with the lowest fire activity (number of fires) and area burned were 2001, 2012 and 2010, 2011, respectively, for GSZ; and 2002, 2019, 2021 and 2001, 2002, 2021, respectively, for FSZ. The year 2018 in GSZ recorded the largest burned area in 21 years, with about 19811.2 km^2 affected and 4719 active points detected. This represented about 11.80% of the total area burned over the period (2001 to 2021), or an average of 825.5 km^2 for 2018. The years 2005, 2013, and 2014 also had large areas burned, while the years with more active fires were 2005, 2006, 2011, 2017, and 2020. The FSZ recorded its greatest burned area in 2015 at 8727.4 km^2 with 5587 active points recorded, which represents an average of 363.6 km^2 of area burned or 7.81% of the total area burned during the study period (2001 to 2021). Other years with significant fire events (area burned and several fires detected) in the FSZ were 2001, 2005, 2014, 2017, 2018, and 2020.

Fire development and intensity from 2001 to 2021

Fire intensity was assessed through the aggregation of data obtained on burned areas from the period 2001 to 2021. This resulted in maps for each month, which were then combined by year. The compilation of these results led to the establishment of fire intensity maps (Figs. 5 and 6) for the districts considered in the different ecological zones. The monitoring of the spatial distribution of burned areas indicated that burned areas were recorded in both ecological zones every year. The MODIS burned

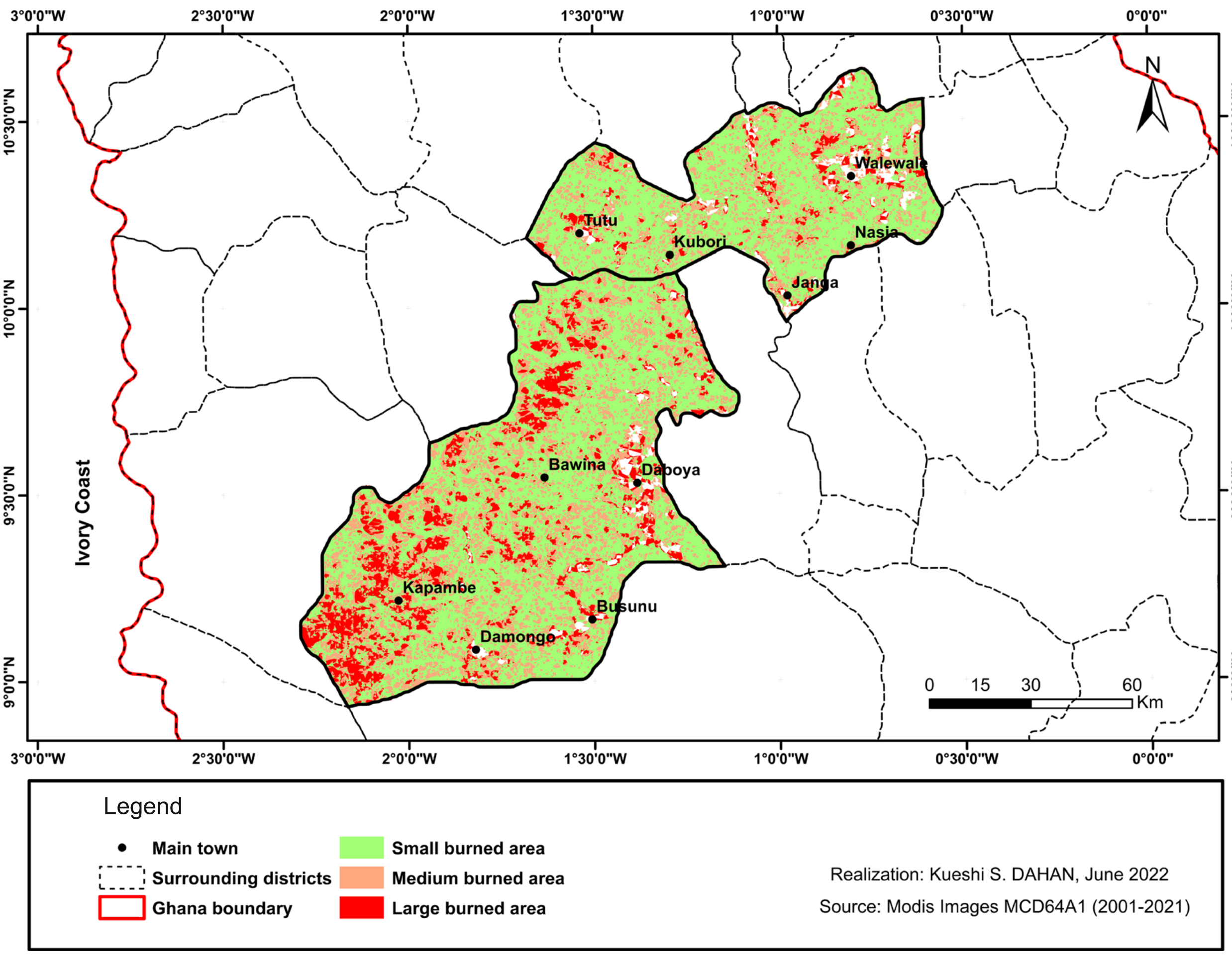

Fig. 5 Fire intensity map of burned area developed for the Guinea-savanna ecological zone study site from data compiled during research to characterize the fire regime for this and the Forest-savanna mosaic ecological zones in Ghana, using a remote sensing approach, during the study period 2001 to 2021. Burned area size is defined as small (<22.4 ha), medium (≥22.4 ha and <100 ha), or large (>100 ha)

area data allowed us to map and estimate the burned area for the period based on the typology of Oliveras et al. (2014). The typology adopted allowed us to identify small burned areas (<22.4 ha), medium burned areas (≥22.4 and ≤100 ha), and large burned areas (>100 ha), reaching a total of 160 220.74 ha for GFZ and 113 697.47 ha for FSZ, from 2001 to 2021. This shows the considerable contribution of fires to the degradation of vegetation cover in the study areas. The location of fire pixels over the 21 years showed a distribution of fire over the whole study area. Generally speaking, this spatial distribution was due to two main factors: climate and the fragility of vegetation due to the use and management of natural resources. The overall proportion of these burned areas was 39.95% of FSZ and 57.13% of GSZ (Figs. 5 and 6).

Frequency and density of fires from 2001 to 2021

The density of the number of fires detected in the ecological zones after spatialization of the data revealed the presence of high fire density in croplands and agricultural areas. Active fire points were used to produce spatial fire density maps (Figs. 7 and 8) with a spatial resolution of 450 m (GSZ) and 694 m (FSZ). In the Guinea-savanna ecological zone, the West Gonja district recorded more active-fire density than West Mamprusi. Each pixel represented the average number of fires that occurred in the area. The overall density in the Guinea-savanna zone and Forest-savanna mosaic zone was estimated at 14 fires km^{-2} and 9 fires km^{-2}, respectively. The occurrence of fires at the level of each zone allowed the calculation of fire frequency within each district. West Mamprusi recorded a fire frequency of 27.22% and West Gonja recorded a frequency of 72.78% in the Guinea-savanna ecological zone. In the Forest-savanna mosaic zone, Sene recorded a frequency of 70.8% and Afram Plains recorded 29.10%. The overall frequencies were 42.87% (Forest-savanna) and 60.05% (Guinea-savanna) (Table 2). Fire-start times (1000 h to 1420 h) in the two

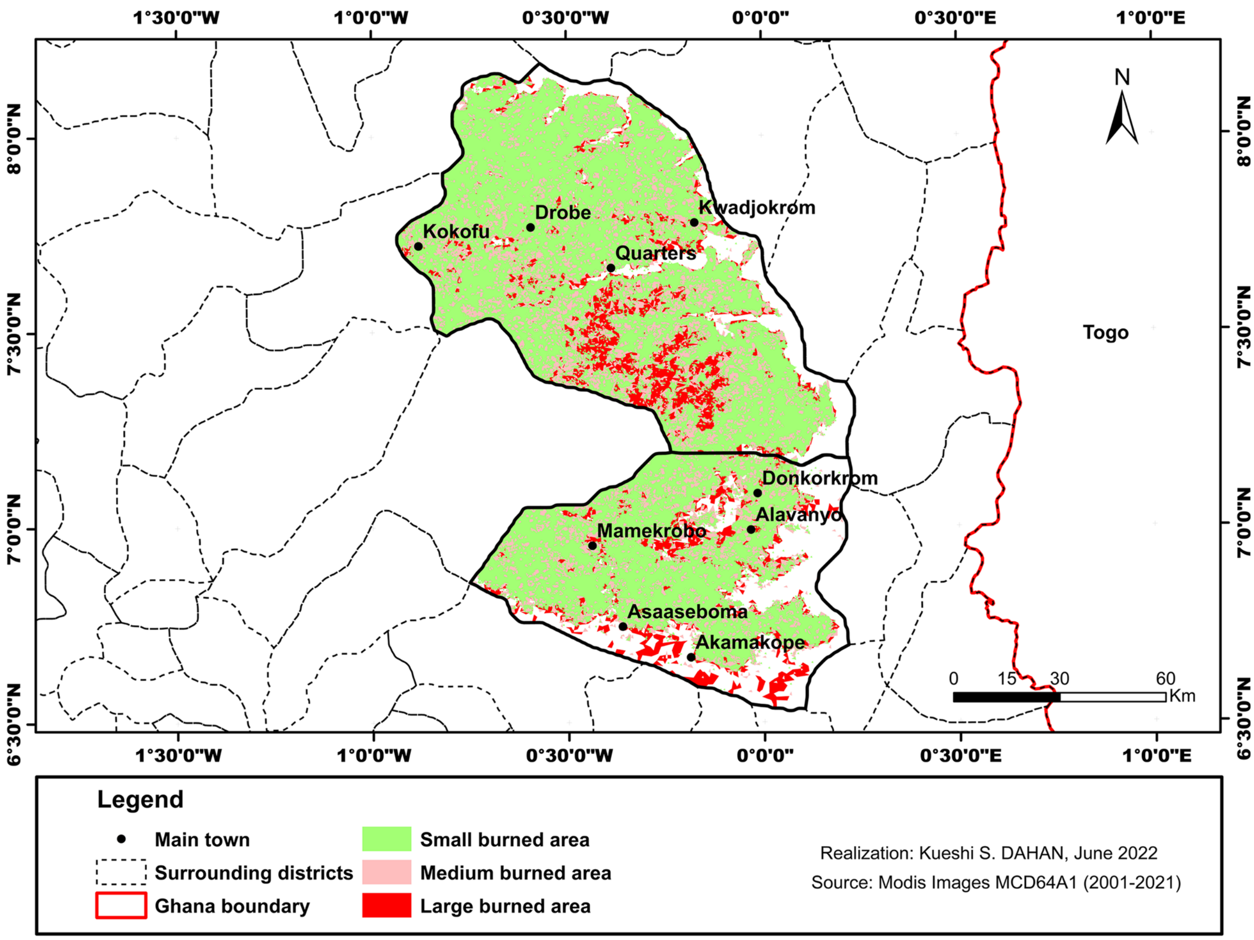

Fig. 6 Fire intensity map of burned area developed for the Forest-savanna mosaic ecological zone study site from data compiled during research to characterize the fire regime for this and the Guinea-savanna ecological zones in Ghana, using a remote sensing approach, during the study period 2001 to 2021. Burned area size is defined as small (<22.4 ha), medium (≥22.4 ha and <100 ha), or large (>100 ha)

zones did not show significant differences, except that GSZ showed that fires started as early as 200 h (Fig. 9).

Statistical analysis of burned areas and active fires in the two ecological zones

Hierarchical Clustering on Principal Components (HCPC) analysis of burned areas

The HCPCP organizes observations by grouping them hierarchically into different classes or subgroups. The aggregation of monthly and annual data, shown in Fig. 10, resulted in four clusters for the Forest-savanna mosaic zone, and three monthly burned-area clusters for the Guinea-savanna zone.

- *Monthly evolution.* Group 1 is composed of January, February, and November clusters in the Guinea-savanna zone (G_1A; Fig. 10A), and the January cluster in the Forest-savanna zone (G_1C; Fig. 10C).

Group 2 , on the other hand, is composed of clusters such as March, October, April, May, June, July, August, and September in the Guinea-savanna zone (G_2A; Fig. 10A), with the December cluster alone constituting group 2 in the Forest-savanna zone (G_2C; Fig. 10C). Group 3 in the Guinea-savanna zone is composed of the December cluster (G_3A; Fig. 10A); whereas, in the Forest-savanna zone, only the February and November clusters are recorded (G_3C; Fig. 10C). Indeed, only the Forest-savanna zone recorded an additional fourth group composed of March, April, October, September, May, August, June, and July clusters (G_4C; Fig. 10C). In sum, these groups were formed according to the intensity of the burned areas: G_2A and G_4C were unburned; G_1C and G_3A were heavily burned; G_1A and G_3C were lightly burned, and G_2C was moderately burned (Fig. 10).

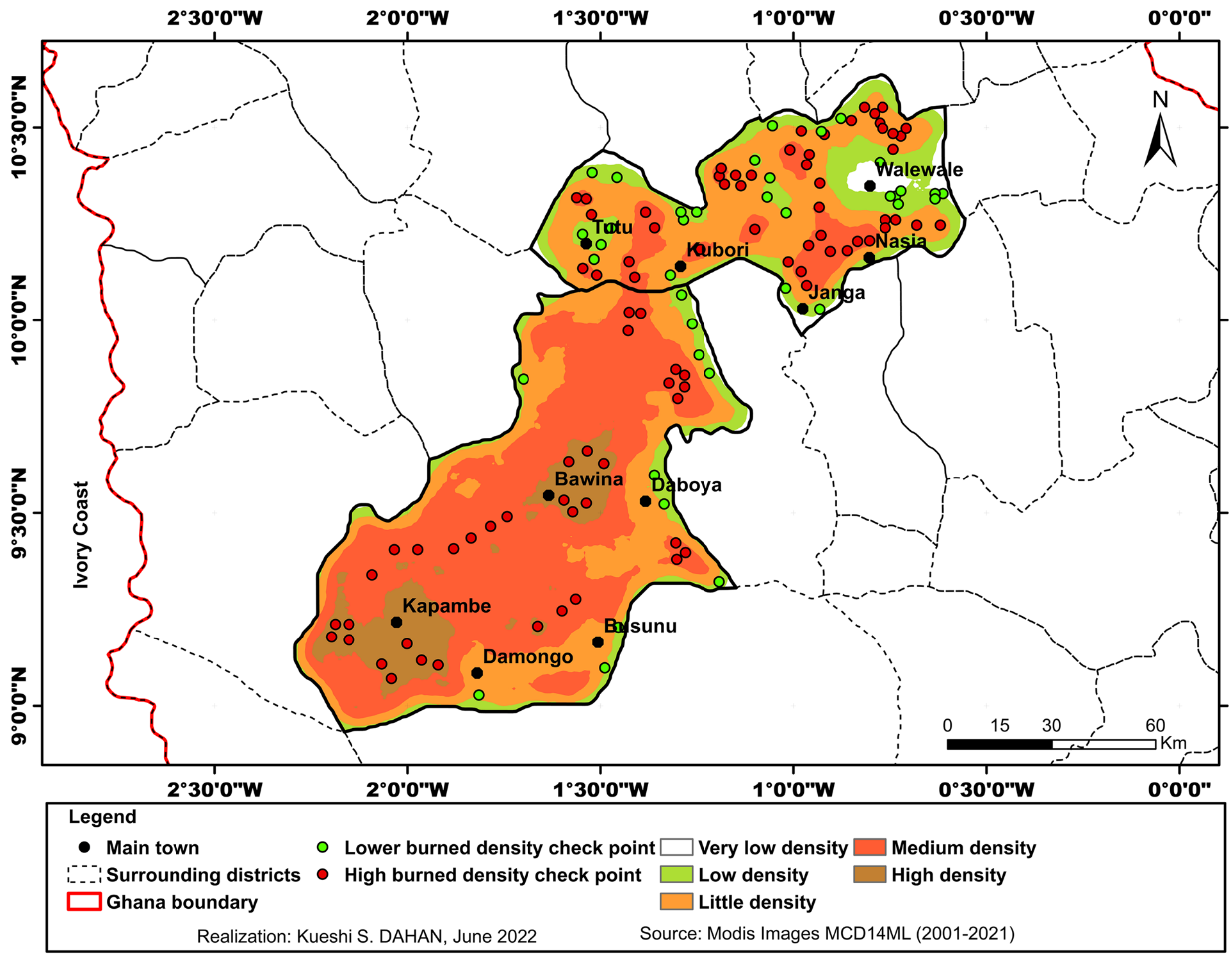

Fig. 7 Number of fires density map developed for the Guinea-savanna ecological zone study site from data compiled during research to characterize the fire regime for this and the Forest-savanna mosaic ecological zones in Ghana, using a remote sensing approach, during the study period 2001 to 2021. The density classification levels are: very low density (<2.33 fires km^{-2}), low density (2.33 to 5.768 fires km^{-2}), little density (≥5.768 to 6.408 fires km^{-2}), medium density (≥6.408 to 7.765 fires km^{-2}), and high density (>7.765 fires km^{-2})

- *Annual evolution.* Group 1 is composed of clusters 2001, 2016, 2002, 2003, 2005, 2014, and 2013 in the Guinea-savanna zone (G_1B; Fig. 10B); clusters 2001, 2020, 2003, 2018, 2013, 2006, and 2008 compose the Forest-savanna zone (G_1D; Fig. 10D). On the other hand, group 2 is composed of clusters in 2004, 2015, 2010, 2008, 2012, 2021, 2009, and 2011 in the Guinea-savanna zone (G_2B; Fig. 10B), with clusters in 2005 and 2015 constituting group 2 in the Forest-savanna zone (G_2D; Fig. 10D). Group 3 in the Guinea-savanna zone is composed of clusters in 2006, 2020, 2007, and 2017 (G_3B; Fig. 10B); while in the Forest-savanna zone, clusters in 2004, 2007, 2012, 2014, 2016, 2009, 2011, and 2010 are recorded (G_3D; Fig. 10ED). Indeed, only the 2018 cluster is recorded in group 4 in the Guinea-savanna zone (G_4B; Fig. 10B); while the Forest-savanna mosaic zone is composed of clusters in 2004, 2007, 2012, 2014, 2016, 2009, 2011, and 2010 (G_4D; Fig. 10D). In sum, these groups were formed according to the intensity of the areas burned (Fig. 10).

Trends in fire active points and area burned by ecoregion (2001 to 2021)

In order to show the trends that might exist in burned areas and the number of fires in the different zones, we performed the non-parametric Mann-Kendall test and the Pettitt test.

- *Mann-Kendall test.* The results (Table 3) show that there were two trends: negative and positive, but both were non-significant. All zones showed a non-significant downward trend in the area burned, and a positive trend in the number of fires detected for

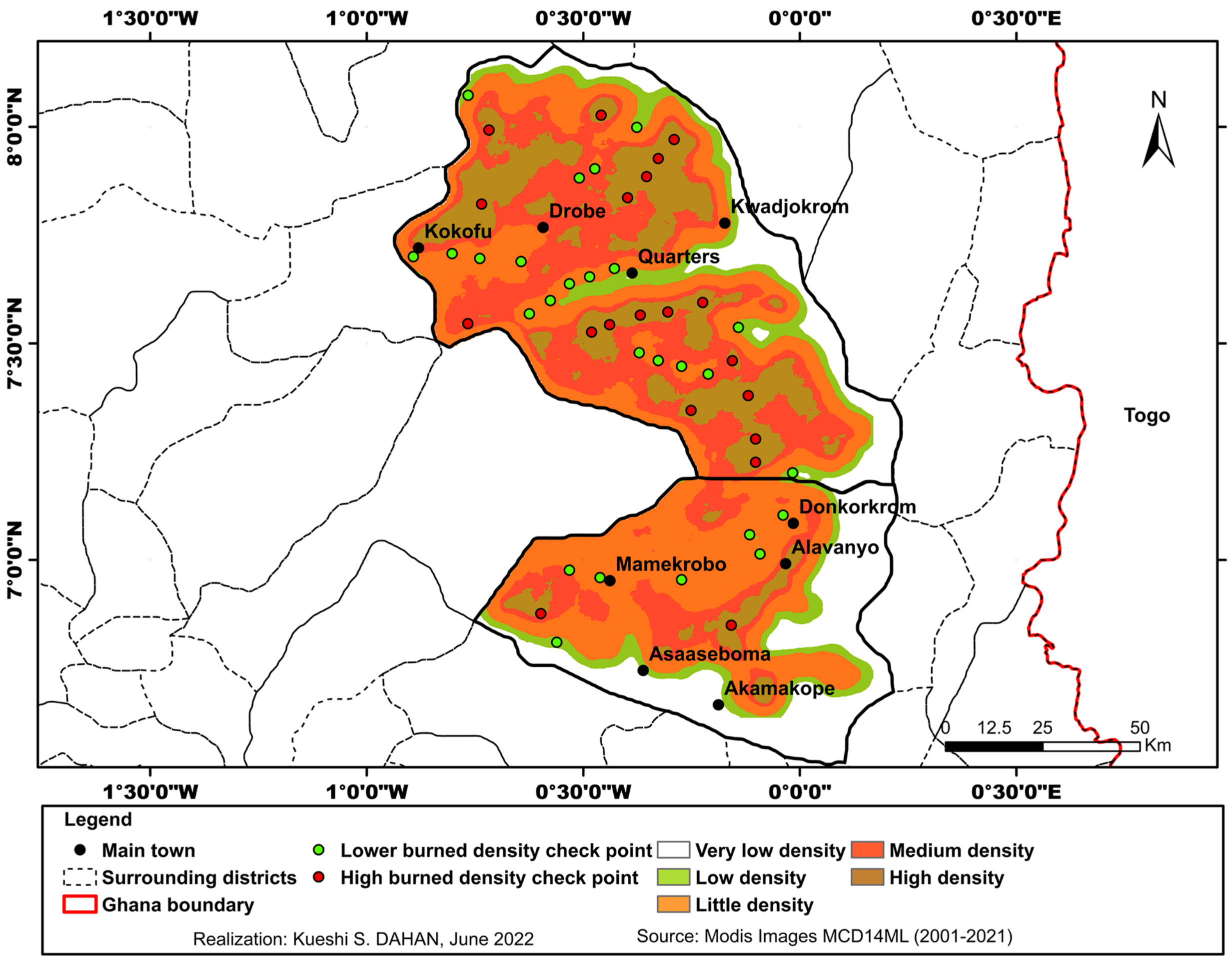

Fig. 8 Number of fires density map developed for the Forest-savanna mosaic ecological zone study site from data compiled during research to characterize the fire regime for this and the Guinea-savanna ecological zones in Ghana, using a remote sensing approach, during the study period 2001 to 2021. The density classification levels are as follows: very low density (<2.33 fires km^{-2}), low density (2.33 to 5.768 fires km^{-2}), little density (≥5.768 to 6.408 fires km^{-2}), medium density (≥6.408 to 7.765 fires km^{-2}), and high density (>7.765 fires km^{-2})

Table 2 Number of active fires (total, frequency, and average) and area burned (total, proportion, and average) data recorded during the study period (2001 to 2021) according to districts within ecological zones (location) in Ghana during research to characterize the fire regime of the area using a remote sensing approach

Location	Number of fires			Burned area		
	Total (*n*)	Frequency (%)	Average (*n*)	Total (km^2)	Proportion (%)	Average (km^2)
Forest-savanna	73 915	42.87	1759.95	111 691.19	39.95	2659.31
Sene	52 403	70.90	2495.38	80 843.46	72.38	3849.69
Afram Plains	21 512	29.10	1024.52	30 847.73	27.62	1468.94
Guinea-savanna	98 501	57.13	2345.26	167 858.37	60.05	3996.63
West Mamprusi	26 812	27.22	1276.76	44 042.81	26.24	2097.28
West Gonja	71 689	72.78	3413.76	123 815.56	73.76	5895.98

the Mann-Kendall test ($P > 0.05$). Considering the different zones, the annual trend of burned areas did not show statistical significance. By analyzing the trend, we noted the presence of an orientation of the curves (Fig. 11), but this did not present monotony. Indeed, the positive Mann-Kendall statistic (S) indicated an evolution of the slope of the trend line, as does the standardized test statistic (Z).

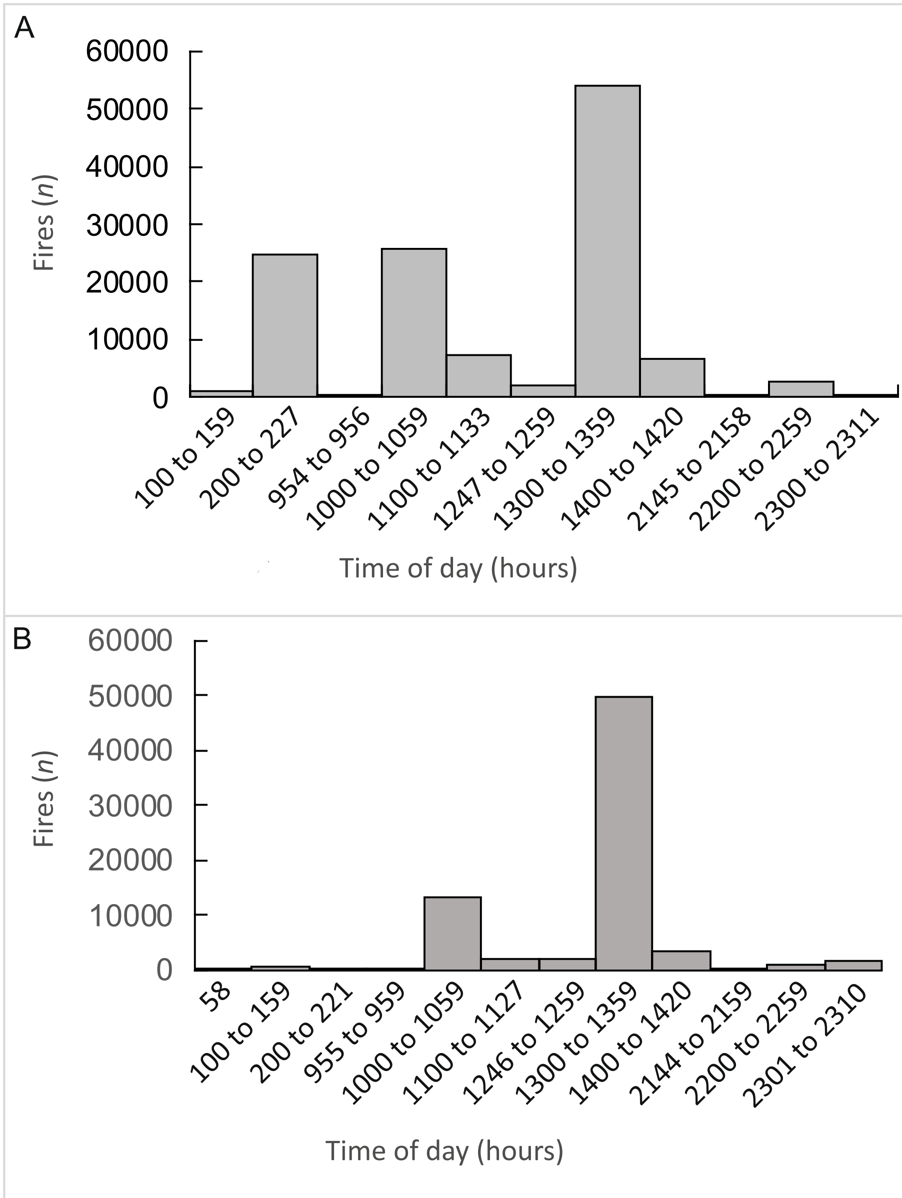

Fig. 9 Average number of fire ignitions recorded per time of day in (A) the Guinea-savanna ecological zone and (B) the Forest-savanna mosaic ecological zone recorded from 2001 to 2021 during research to characterize the fire regime of the two zones in Ghana using a remote sensing approach. This data illustrates periods of time when vegetation in these zones was most prone to fire

However, the significance of the trend (Tau) is invalidated by the probability values found (*P*-values not significant). Thus, the detection of probable break periods was necessary; hence the application of the Pettitt test.

- *Pettitt test.* The Pettitt test (Pettitt 1979) is non-parametric and derives from the Mann-Whitney test (Mann and Whitney 1947). Analysis of the results of this test applied to our study series showed some breaks in the time series of burned area per number of fires, so the null hypothesis (H_0) of no break was rejected with a significance level of 95%, and the alternative hypothesis (H_1, presence of a break) was accepted. The random variability in the burned area per number of fires time series was reflected here by the sinusoidal variation of the Pettitt test variable (U) over time (2001 to 2020). In our case, the H_0 was rejected due to the presence of breaks. The test thus revealed periods of breaks, such as in 2012 (area burned), followed by a decline, and in 2020 (num-

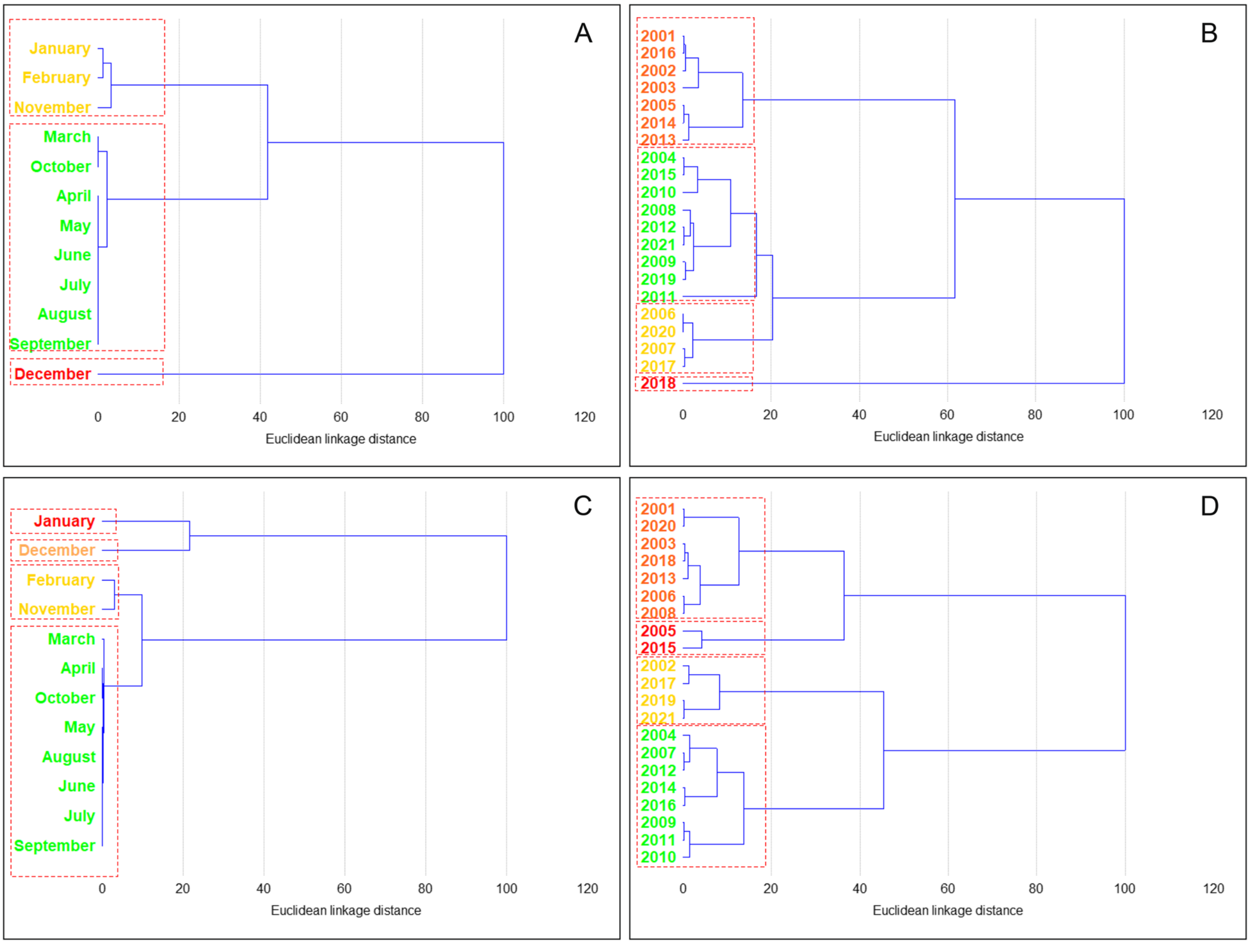

Fig. 10 Hierarchical Clustering on Principal Components (HCPC) of burned area in (**A**), (**B**) the Guinea-savanna ecological zone and in (**C**), (**D**) the Forest-savanna mosaic ecological zone from data compiled during research to characterize the fire regime for these two zones in Ghana, using a remote sensing approach, during the study period 2001 to 2021. The classification shows months or even years that recorded fire according to intensity. The text colors represent the months and years according to the intensity of the burned area: red = high-burned area, yellow = medium-burned area, orange = low-burned area, and green = little or not-burned area. The dashed boxes group the months and years according to the intensity of the areas burned; the blue lines show the similarity of months and years burned in terms of Euclidean distance linkage

Table 3 Mann-Kendall test (S) and standardized test statistic (Z) results for burned area (B_A) and number of fires (N_F) data collected between 2001 and 2021 in two of Ghana's ecological zones (Guinea-savanna, GSZ; Forest-savanna mosaic, FSZ) during research to characterize the fire regime of the area using a remote sensing approach. Kendall rank coefficient (Tau), probability value (*P*), and trend direction (at 95%) are also given. No trend was found to be significant ($P > 0.5$)

Zone	Variable	Tau	S	Z	*P*	Trend
GSZ	B_A	−0.04761905	−10.00000	−0.27177	0.7858	Decreasing
	N_F	0.06666667	14.00000	0.39256	0.6946	Increasing
FSZ	B_A	−0.2190476	−46.00000	−1.3589	0.1742	Decreasing
	N_F	0.1333333	28.00000	0.81532	0.4149	Increasing

ber of fires), followed by an evolution of the trend in the Guinea-savanna ecological zone. For the Forest-savanna zone, the break was observed in 2015 followed by a drop in area burned, while number of fires showed a slight break in 2002 and then an increase until 2021 (Fig. 11).

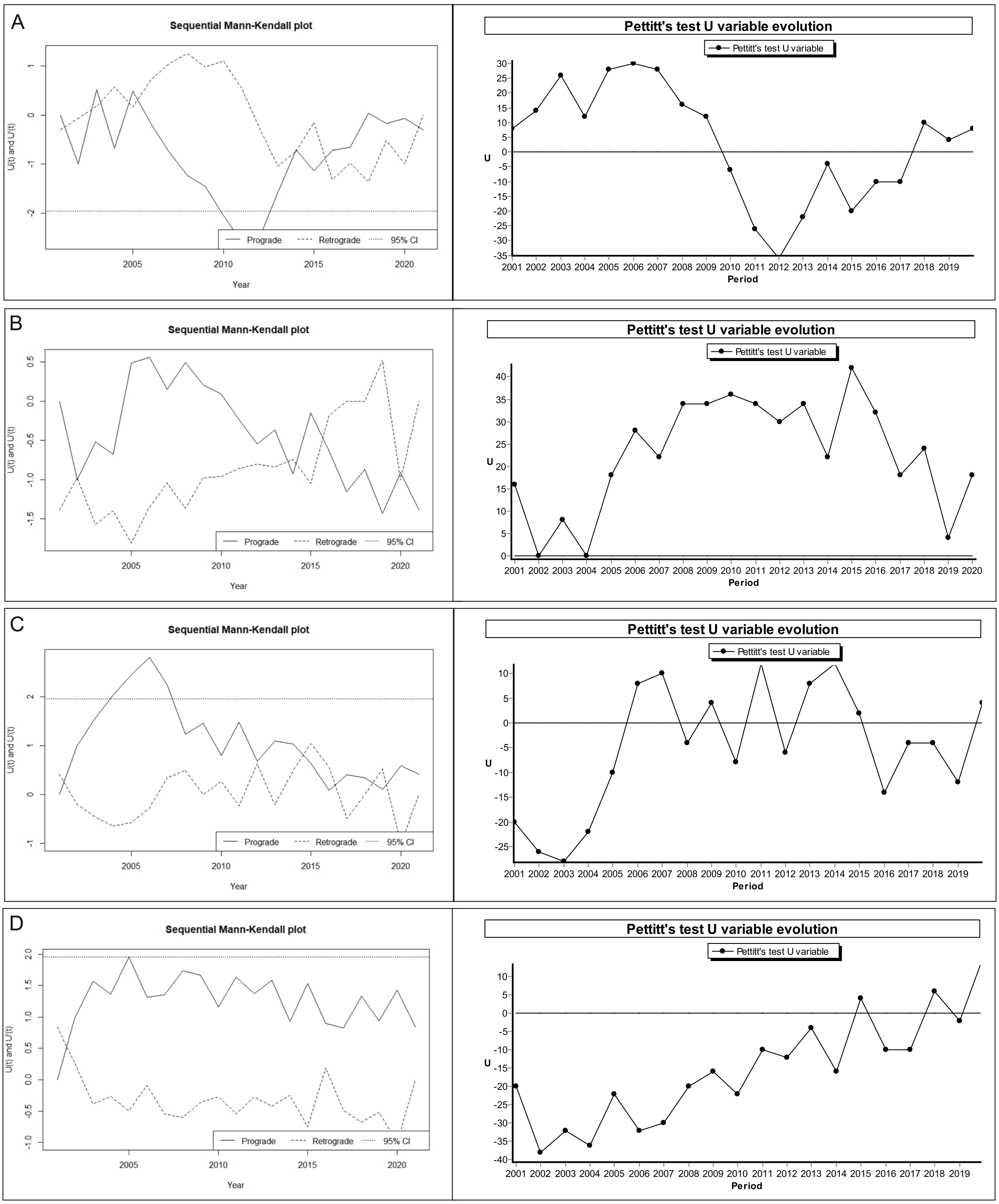

Fig. 11 Mann-Kendall test and Pettitt test plots representing the trend of burned area in (**A)** the Guinea-savanna ecological zone and (**B)** the Forest-savanna mosaic ecological zone, as well as the Mann-Kendall test and Pettitt test plots representing the trend of the number of active fires in (**C)** the Guinea-savanna ecological zone and (**D)** the Forest-savanna mosaic ecological zone in Ghana, from data compiled during research to characterize the fire regime for these two zones using a remote sensing approach, during the study period 2001 to 2021. Sequential values U(t) are standardized variables that have zero mean and unit standard deviation (solid line; prograde series), and U'(t) are the values computed backwards, starting from the end of the series (dashed line; retrograde series). 95% CI = confidence interval of the intersection points of the prograde and retrograde curves

Inter-annual anomalies

The Mann-Kendall test (S) did not show the real increase in terms of burned areas and number of active points, but the calculation of inter-annual anomalies better highlighted the evolution of fire events. Thus, over the study period (2001 to 2021), the burned areas increased by an average of 1.4 km^2 (FSZ) and 4.6 km^2 (GSZ), and the number of active fires increased by an average of 4.7 (FSZ) and 4.4 (GSZ) points per km^2 (Fig. 12).

Discussion

Seasonal evolution of fire events

The results of our study revealed the extent to which fire, in terms of area burned and number of active fires, was seasonally dependent on the different ecological zones that we considered. Fire is used by human populations for the management of agricultural areas; it has become a tradition and is considered to be a mode of land management. Our consideration of total districts, not just specific forest areas, showed the extent and devastating effect of vegetation fire. The most affected months in the Guinea-savanna zone were October, December, and January. These months saw more fires because they correspond to the dry months when the majority of trees and grasses dry up due to climatic conditions. This is in line with findings that have shown that, in African savannas, grass biomass (the major component of the fuel load), fuel moisture content, and weather conditions during burns influence fire regimes, including their frequency and intensity (Bloesch 1999; van Wilgen et al. 2004; Govender et al. 2006). Our research showed a peak in burned areas and the number of fires recorded in December; the period from November through January—the dry period—recorded considerable fire damage. The entire period of tree leaf loss (November through March) showed more marked fire activity due to climatic factors such as the annual advent of Harmattan (a dry, dust-laden continental wind) that increase the flammability of vegetation and the spread of fires (Goula et al. 2012). On the other hand, Husseini et al. (2020) showed that fire occurrences within forest reserves usually peak in January in mid dry season. Forest guards and range supervisors attributed this phenomenon to the abundance of dry leaf litter on the forest floor, serving as fuel, during these periods. This example is more specific, given its focus on one type of ecosystem (a protected area); our study included all ecosystems present in the ecological zones. Kugbe et al. (2012) showed that November, December, and January are the months most affected by fire, without, however, specifying the month in which fire events are most intense. Wildfire event seasonality is highly attributable to the climate type that prevails in each area. Thus, agricultural activities, which are also related to climate, contribute to fire outbreaks as farmers prepare the land during the dry season in anticipation of the rainy season. These anthropogenic activities are common in the two ecological zones studied (GSZ, FSZ). Apart from periods of intense fire activity, months with low burned areas and number of fires were considered to be early (August, September, and October) or late (February, March, and April) fire periods in our study sites. Early- and late-fire seasons are times when specific fire-related activities such as hunting begin. Similar findings were made by Etienne (1971) and Bruzon (1994), who observed the use of wildfire for hunting at the beginning or end of dry seasons. These scenarios are generally the same in both ecological zones because of their homologous floristic composition. However, it is necessary to qualify them because savanna is dominant in the Guinea-savanna zone; whereas, in the Forest-savanna zone, it is a mosaic of forest and savanna. Even though fire activity is low during late fire periods, fires burn more intensely because of the low moisture content of the vegetation and tend to burn more areas than early fires (February, March, and April). These findings are in line with the observations of Nielsen and Rasmussen (2001) and Govender et al. (2006). The low number of wildfires after March is due to the regeneration of vegetation, increasing moisture content, with the first rains, which are generally more intense in the Forest-savanna mosaic zone (bimodal regime), and that evapotranspiration at this time begins to decrease (Guiguindibaye et al. 2013). It should be noted that charcoal production and forest logging companies (Westerhoff and Smit 2009) are observed in these study areas, and their activities contribute to these vegetation dynamics (Obiri et al. 2014, Nketiah and Asante 2018). It is also necessary to take into account the topography of the area. Its high relief favors high wind speed, which is a fire acceleration factor. On the other hand, the savanna of West Mamprusi has little vegetation and is less rugged, which is why anthropogenic pressures have less effect, even though the climate remains the same. The Forest-savanna mosaic zone, also called the transition zone, is considered the granary of Ghana in terms of agricultural production (Titriku 1999). It benefits from a climate more or less favorable for agriculture, which explains the decrease in its burned area. In addition, it is also worth noting the presence of a lake, which is a source of soil moisture; increased humidity slows down the spread of fires in rural areas. However, fire activity (active fire points) remains very present, reflecting the intensity of agricultural activities as a factor in the spread of fire (Agyemang et al. 2015, Nindel 2017).

In all ecological zones, average annual temperatures are estimated to increase between 0.8 °C and 5.4 °C between the years 2020 and 2080. Within the same period, average

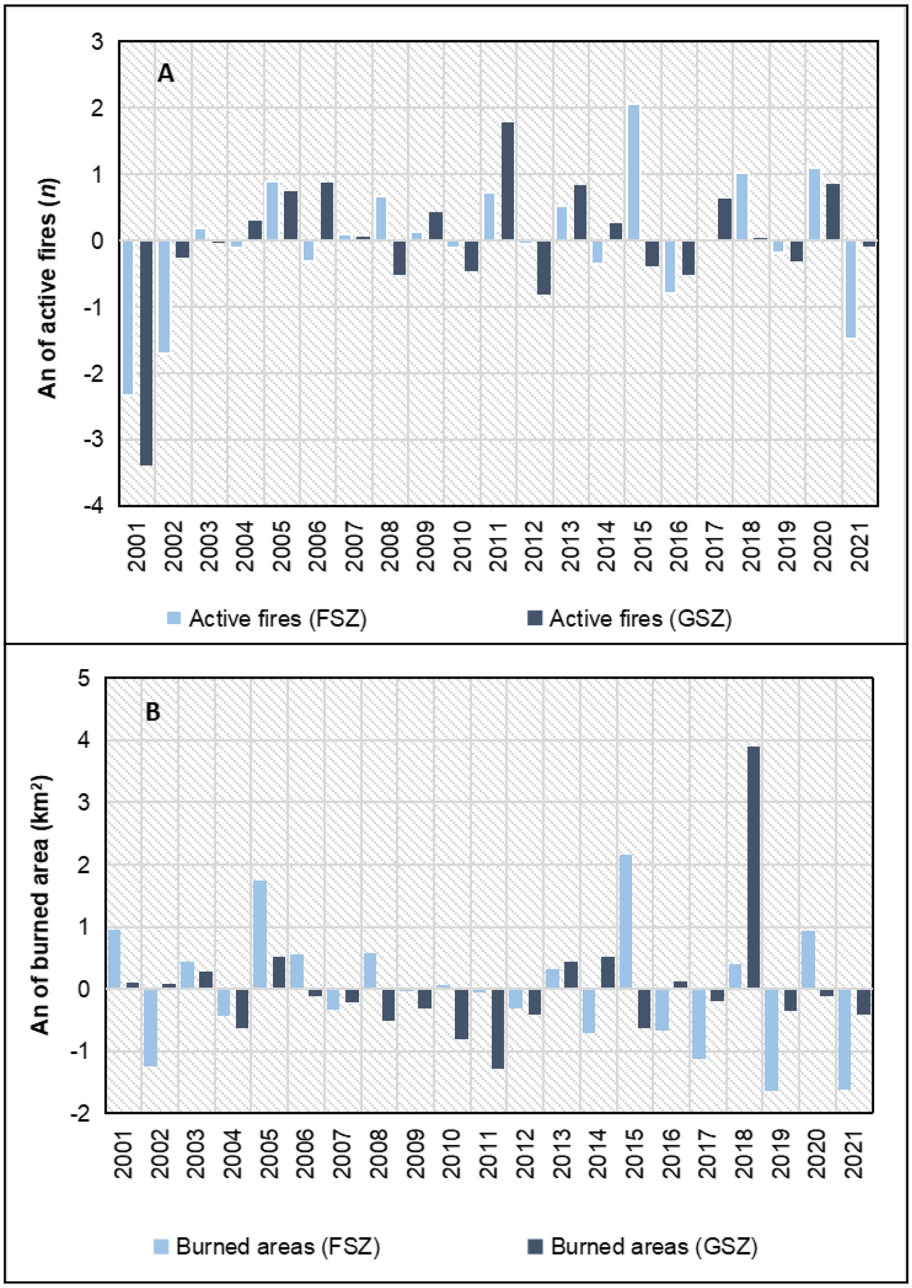

Fig. 12 Inter-annual anomalies (An) of (**A**) the number (*n*) of active fires and (**B**) burned areas (km^2) in Forest-savanna mosaic (FSZ) and Guinea-savanna ecological zones (GSZ) in Ghana, recorded from 2001 to 2021, during research to characterize the fire regime of the two zones using a remote sensing approach

annual rainfall is estimated to decline by between 1.1 and 20.5%. Such a climatic trend could, in the long run, modify seasonal behavior of fires and thus have more impact on the vegetation of these different areas; under a warmer climate in the coming decades, fire will be the main cause of vegetation dynamics (Keane 2013). Similarly, daily start times of anthropogenic fires show that local communities recognize that weather determines the success of fire as a tool and utilize that fact. These periods of the day (1000 h to 1400 h) are the hottest and favor maximum fire action.

Inter-annual evolution of fire events (2001 to 2021)

The remote sensing-based approach used in our study to characterize the fire regime in GSZ proved to be sufficiently accurate to inform decision-makers (i.e., the Ghana Fire Service) regarding fire management in these ecological zones. This study, which was based on a 21-year time series of burned areas and active fire points (2001 to 2021), revealed a downward trend in burned areas and an upward trend in the number of fires in the zones under consideration (GSZ and FSZ), which are statistically insignificant. On the other hand, the evaluation of the anomalies shows an increase in fire activity in terms of surface area and number of active points. These trends do not show monotonicity because of a sinusoidal evolution. Some similar studies have observed declining trends in the number of fires and areas burned in sub-Saharan Africa over the last decades (Giglio et al. 2013; N'Datchoh et al. 2015). Andela et al. (2017) showed a significant downward trend in the number of fires, fire size, and area burned in Africa between 2003 and 2015 using MODIS products, which is not the case in our study where only the area burned was seen to decrease. This trend could be due to slash-and-burn agriculture that takes place every year in those areas. This regular agricultural practice could be at the root of the increase in active fires detected, even if their presence does not contribute much to the burned area over time, probably due to the resultant decrease in flammable area.

Stanturf et al. (2011) was one of the few research studies in Ghana that considered large ecological zones with districts most vulnerable to climate change as targets. Their analysis of MODIS images showed that large areas were burned each year. The areas with a high probability of being burned represented the areas with vegetation cover sensitive to wildfire. Some years were particularly marked by fire events in the different ecological zones (2018 in GSZ and 2015 in FSZ). The overall proportion in the zones (39.95% for Forest-savanna and 57.13% for Guinea-savanna) in terms of fire intensity (area burned) showed that the savanna zones are threatened by the risk of fire and remain more fragile than other ecological zones. Similarly, with regard to districts by zone, West Mamprusi recorded a fire frequency of 27.22% and West Gonja recorded a frequency of 72.78% in the Guinea-savanna ecological zone; and in the Forest-savanna zone, Sene had a high frequency of 70.8% and Afram Plains a frequency of 29.10%. The overall fire frequency was 42.87% (Forest-savanna) and 60.05% (Guinea-savanna). The year 2018 coincides with the period when Ghana lost about 12 298 ha of its vegetation cover (Inter-Réseaux Développement Rural 2019). Furthermore, the two zones are similar in the number of metric tons of charcoal each produced: 34.4% (GSZ) and 26.7% (FSZ) of the national production (Nketiah and Asante 2018). This cutting and burning of large trees can significantly contribute to an increase in the area burned (e.g., 2018). The use of fire for charcoal burning and hunting in the region is similarly confirmed by the work of Amoako and Gambiza (2022).

Indeed, the assessment approach used in this research may overestimate or even underestimate the assessment of burned areas due to the 250 m spatial resolution of the MODIS MCD64A1 image. Omission errors occur when spatial extent is insufficient or too fragmented to be discerned as wildfires (Roy et al. 2005), or when fires are hidden by cloud cover (Giglio et al. 2020). In a study in Ghana based on satellite images (2002 to 2003; UNDP 2008), a large part of the vegetation in the north had disappeared. It showed that slash-and-burn cultivation and agricultural over-exploitation of cleared land were identified as the main causes of this loss of vegetation cover (UNDP 2008). After 2003, 2018 saw a larger area burned, which could be due to the weakening of forest resources due to agricultural and logging activities. Population growth and poverty are often linked to natural resource degradation in fire-prone savanna, as an increasing number of poor farmers are thought to be drawing on the forest for slash-and-burn agriculture (Afikorah-Danquah 1997). This observation was made in the GSZ, specifically in the West Gonja district, where forest is burned to create fields for cultivation.

Fire activities recorded in the Forest-savanna zone could be due to pressure on resources as well as agricultural practices that are being accentuated by the arrival of settler-farmers from the northern zone of Ghana due to impoverished land (e.g., the majority of Dagaba settled in the Brong Ahafo Region are smallholder farmers who migrated), in search of better agro-ecological conditions (Afikorah-Danquah 1997). It was found that, during the 2000 Ghana census, 18% of the farming population in the northern zone migrated to the Brong Ahafo Region of the FSZ (GSA 2005).

The Guinea-savanna and Forest-savanna mosaic ecological zones have seen an increase in the number of fires due to a lack of enforcement of laws regulating wildfires. This observation was made by the research of Kusimi and Appati (2012) during the period 2002 to 2003. Their research revealed that the continued prevalence of fire-related activities was due to laxity in the implementation of the laws regulating wildfires, because of a lack of personnel and logistics of government agencies in the district to combat the problem. The characteristics of the types of land-use units would also be an important factor in the differences observed in terms of area burned in the ecological study areas, within the land management systems involved. Depending on the intensity, grazing can keep the grasses short, thus reducing the occurrence of fires in the following season (Govender et al. 2006; Archibald et al. 2010). Thus, the observed trends of vegetation fires should be analyzed from several angles, namely climatic and environmental angles, as these are the parameters considered to be the greatest in influencing fire behavior in the tropical zones (Flannigan et al. 2009; Archibald et al. 2010; Turetsky et al. 2015; Santín et al. 2016; Walker et al. 2019), in populated areas (Frost 1996; Ribeiro et al. 2008; Tarimo et al. 2015), and in unpopulated areas (Flannigan et al. 2009; Turetsky et al. 2015; Santín et al. 2016) areas. Also, the nature of the vegetation cover in terms of floristic composition and type of land use units should be taken into account. Studying these angles could better elucidate causes and observed trends of fire events in the study period considered (2001 to 2021). Thus, according to the results, the burned areas are decreasing, which leads to the following questions: is this caused by the degradation and reduction of vegetation in these areas or by the reduction of activities related to the use of fire by local populations? These questions need to be investigated, for more clarity on the contribution of fire to land cover degradation.

Conclusions

Our study, using a remote sensing approach, assessed the spatial and temporal fire events in the GSZ and FSZ in Ghana. Four districts, namely West Gonja and West Mamprusi in the Guinea-savanna ecological zone, and Sene and Afram Plains in the Forest-savanna mosaic ecological zone, were assessed. This scientific assessment focused on fire regime characteristics such as seasonality, intensity, density, burned areas, frequency, and trends during the study period from 2001 to 2021. Our approach allowed us to show that the spatial distribution did not follow a defined trend, nor did the detected active points. However, the evaluation of the inter-annual anomalies showed the evolution of the burned areas as well as the number of active fires, even though the statistical significance was not pronounced. This trend measurement made it possible to elucidate the extent of fire, pinpointing the particularly affected years such as 2018 in the GSZ, and 2001, 2005, 2015, 2017, 2018, and 2020 in the FSZ. The months of December and January in both areas should be closely monitored by natural resource protection and conservation agencies in Ghana (e.g., Ghana Fire Service). It was possible to quantify the area burned within different ecological zones over the entire period under consideration by using the remote sensing approach that has so far been poorly implemented in Ghana. However, this research failed to map the actual causes of change, which should be addressed in future research.

Overall, the GSZ was the most affected by fire events and must continue to be given special attention. However, the FSZ is in a state of degradation due to anthropogenic pressures, as revealed in the literature, and could become the most fire-affected area in the decades to come if appropriate measures are not taken. This supports our initial hypothesis on the spread and eventual impact of fires in the FSZ. As fire activity increases, weather (climate) becomes another factor to be closely monitored to increase the reliability of wildfire prediction to provide earlier warning and preventative measures. With our current lack of knowledge of which land-use types are most vulnerable to wildfire, it is essential to continue research in this direction to better reframe policy decisions on sustainable natural resource management to better minimize costs. Ultimately, Ghana should use this kind of inventory to establish a sound approach to wildland fire risk management, as many areas depend on it. In view of our results, we call on forest resource management structures, village management committees, and NGOs to intervene more regularly during periods when fires are likely to occur. The Ghana Fire National Service and Forestry Commission of Ghana should collaborate closely with local representatives to implement guidance, monitoring, and supervision programs at national, regional, and local levels, in view of the high number of fire events in these areas.

Acknowledgements
This research was made possible through funding support from the Islamic Development Bank. The authors are particularly grateful to the University for Development Studies, West African Center for Water, Irrigation and Sustainable Agriculture for providing logistics to facilitate the completion of this paper. Special thanks to L. Burk for her expert eye on the form and linguistic aspects of this article.

Authors' contributions
K.S.D developed the theoretical framework, performed the data processing, and performed the analytic calculations. R.A.K. supervised the methodology, and R.H. and R.A.K. contributed by reviewing to the final version of the manuscript.

Funding
This research was made possible through funding support from the Islamic Development Bank.

Availability of data and materials
The data that support this study are available at https://doi.org/10.5281/zenodo.7749206.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
The authors agree to the publication of this study without restriction.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Department of Environment and Sustainability Sciences, Faculty of Natural Resources and Environment, University for Development Studies, West African Centre for Water, Irrigation and Sustainable Agriculture, Nyankpala-Campus,

P.O. Box TL1882, Tamale, Ghana. [2]West African Centre for Water, Irrigation and Sustainable Agriculture, University for Development Studies, Nyankpala-Campus, P.O. Box TL1882, Tamale, Ghana. [3]Department of Environment, Water and Waste Engineering, University for Development Studies, Nyankpala-Campus, P.O. Box TL1882, Tamale, Ghana. [4]Department of Forestry and Forest Resources Management, Faculty of Natural Resources and Environment, University for Development Studies, Nyankpala-Campus, P.O. Box TL1882, Tamale, Ghana.

Received: 24 November 2022 Accepted: 5 June 2023
Published online: 17 July 2023

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