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Fire risk assessment, spatiotemporal clustering and hotspot analysis in the Luki biosphere reserve region, western DR Congo

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ABSTRACT

This paper analyzes active fires from 2001 to 2019 in and around the Luki Biosphere Reserve, western DR Congo to assess fire risks. In this study, we used descriptive statistics to assess fire events, Getis-Ord G hotspot analysis to define the spatial patterns presented by the fire events. Diagnostics for spatiotemporal clustering of fires location and space-time interaction were assessed the spatiotemporal K function. MODIS data from 2001 to 2019 revealed 4602 fires events and 150,132 ha burned, corresponding to 42.6% of the study area. The results of this study show that the peak of fires was recorded in 2013 and fires are mostly recorded every year during the dry season from June to September. They occurred mostly between Noon and 01:00 PM local time. Fires that occurred in the region had low radiative power with the mean value of 23.5 Mega Watts. The Hotspot region where fires take place is located in the South-Eastern part of the studied area exhibiting a significant spatiotemporal clustering (p value = 0.012). Fires are mainly of 2 origins: annual savannah clearing and agriculture fires. The results of this research will help decision making with proactive preventive measures over time and space.

Introduction

Forest fire is an integral part of ecosystem dynamics (Abdollahi et al., 2018) and is considered as a natural regulator of natural landscapes since immemorial times (Rodriguez-Trejo and Fulé, 2003; San-Miguel-Ayanz et al., 2012). Africa is the most fire-active continent due to high frequencies of wildfires (about 28,000 fires per year) that affect landscapes over large areas (Eva et al., 2003; Kana and Etouna, 2006). In the Democratic Republic of Congo an average of 2824 fires per year were recorded from 1996 to 2001 (Eva et al., 2003) and the Central Kongo Province is among the most active fire regions mainly due to the predominantly savannah-dominated ecosystem.

Wildfires play an important role in ecosystem balance by reviving healthy species, extinguishing pests and diseases, and providing nutrients for better regeneration dynamics (Abdollahi et al., 2018) especially in savannah ecosystems dynamics (Mayaux et al., 2003). The negative effects of fire are most important for forests with slow regeneration rates. For savannahs, however, the most dramatic effect is related to the rapid spread of fire over large areas (Devineau et al., 2010; Kanvaly et al., 2013). Fires contribute to the global warming through the release of trace gases (CO_2, CH_4, NMHC and NOX) acting as Greenhouses Gazes through biomass combustion (Frost, 2021; FAO, 2006; Abdollahi et al., 2018). Fires also contribute to the destruction of neighborhoods, critical infrastructure, and biodiversity (Ahmed et al., 2018). It increases respiratory diseases by affecting air quality (Abdollahi et al., 2018).

Among the key factors involved in the increasing of fires in the Central Kongo Province, population growth plays a key role (Bamba, 2010). The population density increased from 52 inhabitants/km^2 in 2001(Tshibangu, 2001) to about 90 inhabitants/km^2 in 2015

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(Ministère Plan, 2015). Indeed, the demand for agricultural land increases proportionally with population growth (Ramade, 1984; Tchatchou et al., 2015), slash and burn agriculture, which is the main agriculture type in the DR Congo, will remain the key driver of current and future deforestation trends (Duveiller et al., 2008; Ickowitz et al., 2015). The rate of natural environment conversion into pastoral and agricultural systems as well as the development of residential areas, infrastructure and traffic networks continue to increase (MECNT, 2009; FAO, 2006; Iyongo, 2013; Ministère Plan, 2015).

The poverty rate (69.8%) (Ministère Plan, 2015) also plays an important role in fire activity in the region. The population, with no other source of income, returns to the forest in search of livelihoods. This leads to inappropriate use of resources amplifying degradation through the direct impact on land use and landscape configuration (Bamba, 2010). The natural processes of vegetation succession are then disrupted by anthropogenic activities through the frequent burning of savannahs and forests (Vink, 1983; Achard, 2002).

Several studies documented fire management using remote sensing both at regional level (Frost, 2021) in Southern Africa, (Eva et al., 2003) in Sub-Saharan Africa as well as in some African countries such as Burundi (Elias and Didier, 2019), Ivory Coast (Kouakou et al., 2013), Burkina Faso (Caillault et al., 2010), Togo (Afelu et al., 2016), W Park configuration (Eva et al., 2003) and DRC (Lutete et al., 2016). For more than thirty years, remote sensing imagery combined with GIS provides information on the spatial and temporal dynamics of fire events at national and local scales (Eva et al., 2003; Mbow, 2009; Parajuli et al., 2015). This approach is used to characterize fires, to determine their spatial and temporal distribution and to determine their frequencies in order to optimize their benefits and to guide strategies for their management (Grégoire et al., 2003). Given the extent of the area covered and the accessibility, spatial remote sensing is the best tool to make a regular inventory of fire events (location, date, time), thus contributing to their daily management. The spatiotemporal methods for analysis of fire clustering have also become a focus of considerablae attention (Pew and Larsen, 2001; Corcoran et al., 2007; Asgary et al., 2010; Ceyhan et al., 2013) but this field of research is still less exploited in DR Congo and particularly in and around Luki BR. Given the high recurrence of fires in the region, studying the fire regime will allow managers to put in place management measures appropriate to the threats facing the Luki Biosphere Reserve, one of the three biosphere reserves in the DR Congo. For a better understanding of the processes behind resource degradation in the Luki Biosphere Reserve, the study area took into account the reserve and its surroundings over 20 km.

This research therefore, locates, characterizes, quantifies and determines spatiotemporal clustering of fires using data from the Moderate-Resolution Imaging Spectroradiometer (MODIS) from 2001 to 2019.

Materials et methods

Study area

Our study area is located between 5.3–5.9°N latitude and 12.8–13.8°E longitude in and around the Luki Biosphere Reserve, in Kongo Central Province, western DR Congo (Fig. 1). The Luki BR is dominated by Aw5 Climate type (Köppen-Geiger in 1923) characterized by two very contrasting seasons: the rainy season starting mid-October up to mid-May with a short dry spell in February and the dry season going from mid-May to mid-October (Mankoto and Maldague, 2005; WWF-RDC, 2009). Data obtained from weather station Luki revealed that from 2001 to 2019 the mean average temperature varied from 21 to 27 °C while the total annual precipitation varied from 950.5 to 1953.7 mm. During the same period, the dry months varied from 4 to 8 months with the peak of the drought in the years 2012, 2013 and 2019.

In Luki BR the vegetation is mainly a dense humid and semi-deciduous forest with about 1096 species dominated by flowering plants (1055 angiosperms) (Lubini, 1997). The peripheries of the Luki BR are mainly dominated by savannahs, which are constantly subject to fires. The Luki Reserve belongs entirely to the catchment area of the Luki River; from which it takes its name (WWF-RDC, 2009). In recent years, the population of Luki and its surroundings has changed significantly. With an average population growth rate of 2.18% between 2003 and 2018 name (World Bank, 2019), it has grown from 28,590 inhabitants in 2003 (Nsenga, 2001) to approximately 117,849 habitants in 2019.

Data source

Incidences of fire in the study area from 2001 to 2019 were analyzed using Active Hotspot data and burned areas acquired from NASA's Fire Information for Resource Management System (FIRMS) (Elias and Didier, 2019; Boschetti et al., 2015). In order to better understand and discuss the remote sensing data, interviews were conducted with communities and climate data from January 2001 to December 2019 were also collected to evaluate the probable correlation with the fire incidences.

Active fires and burned areas data

A large number of studies have demonstrated the value of optical and thermal remote sensing for quantifying fire occurrences and the areas affected by fire (Giglio et al., 2006). The active fire data were provided by Earth Observing System (EOS) of NASA (National Aeronautics and Space Administration) fire (Eva et al., 2003). *MODIS* is the first sensor that included fire monitoring capabilities in its design and up to now remains of the most important data sources for global mapping of both fire locations and burned areas fire (Giglio et al., 2006). It provides data at lower spatial resolution (1 km) but with a higher acquisition frequency (daily). These data are produced by NASA's Fire Information for Resource Management System (FIRMS) and provided by the University of Maryland (Elias and Didier, 2019; Boschetti et al., 2015). The data were downloaded from https://firms.modaps.eosdis.nasa.gov/map in Shape (*.shp) format dated from 2001 to 2019.

MODIS sensors are mounted Terra and Aqua satellites. Terra provides data from February 2000 to the present and Aqua has been providing data from June 2002 to the present (Eva et al., 2003; Broucke, 2009; Müller and Suess, 2011). Terra crosses the equator at about 10:30 am and 10:30 pm each day while Aqua crosses over the equator at about 1:30 pm and 1:30 am every day (Giglio et al., 2006; Müller et al., 2013; Elias and Didier, 2019). In our study area almost all the fires were recorded by the Aqua satellite 97.39%.

There are several MODIS products for active fire detection. The MOD14 product series based on Terra sensor data and MYD14 based on Aqua sensor data are the most widely used (Broucke, 2009). These are "Level 2 Fire products" (Boschetti et al., 2015). The detection of fire points by MODIS satellites is fully automated (Giglio et al., 2003; Caillault et al., 2010) and allows the production of daily fire information over the entire earth. MODIS NRT (MCD14DL) active fire products are processed using the standard MOD14/MYD14 Fire and Thermal Anomalies (Boschetti et al., 2015).

The fire detection algorithm is fully automated and identifies pixels with one or more actively burning fires for the entire globe. Each MODIS active fire location represents the center of a 1 km pixel that is marked by the algorithm as containing one or more fires in the pixel. These pixels are commonly known as "fire pixels". The MODIS active fire product detects fires in 1 km pixels burning at the time of overpass under relatively cloudless conditions using a contextual algorithm (Giglio et al., 2003; Müller and Suess 2011). The probability of detecting a fire is highly dependent on its temperature, the area over which the fire spreads and the angle of view of the satellite relative to the nadir. Local weather conditions also influence this probability (Giglio et al., 2003, 2018).

Active fire observations from MODIS satellites generate a range of products including the geographical coordinates (of a fire) which are provided in Coordinated Universal Time (UTC), the Radiative Power of

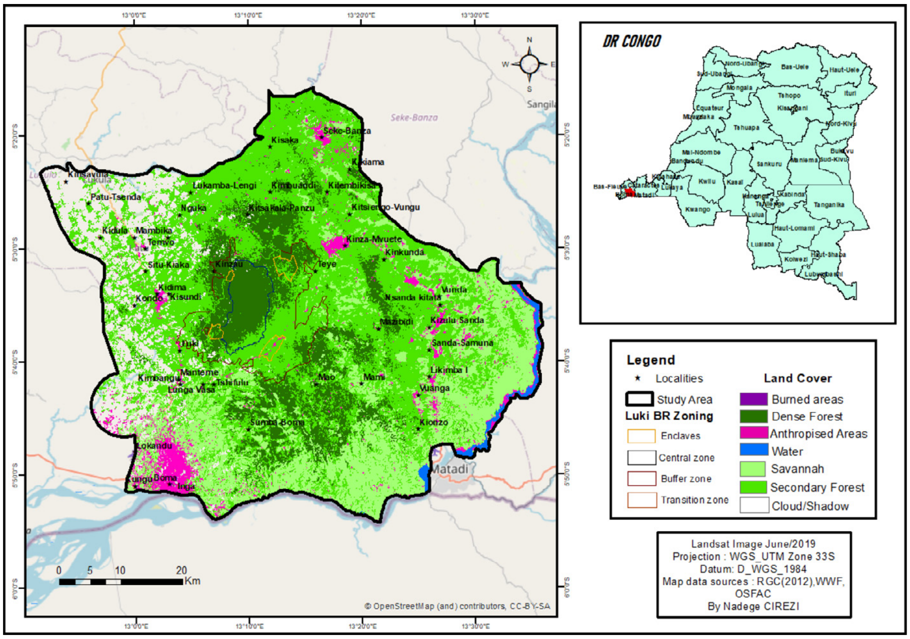

Fig. 1. Study area.

a fire expressed in megawatts (MW), the date and time of the fire registration, etc. The MCD14DL data consists of fire points and is available in several downloadable formats: TXT, SHP, KML, WMS but only the TXT and SHP files contain all the attributes. These data are also provided through LANCE FIRMS Fire Email Alerts (Giglio et al., 2018).

Survey data

A survey was carried out on a sample of 96 residents in and around Luki BR to understand remote sensing data and to document and characterize fire use and management in the area. A sampling method based on the binomial law formula proposed by Dagnelie was used for that purpose (1998).

Climate data

Climate data were collected daily by meteorological observers at 3 h intervals (6 a.m., 9 a.m., 12 p.m., 3 p.m. and 6 p.m.) at the Luki station. The daily logs and weather observation logs provided a database covering the 19-year period (2001–2019). Rainfall and temperature data were also recorded for that period.

Data processing

For locating active fires the confidence scale varying from 1 to 100 was taking into account. The confidence levels are based on quantitative adjustments of the algorithm in the detection process (Giglio et al., 2003, 2006, 2018). So,to obtain a proven fire base, fire points with a confidence less than 30% were dropped as they were considered unreliable (Caillault et al., 2010; Giglio et al., 2018).

For fire characterization and quantification excel descriptive analysis was used to determine the annually, monthly and daily repartition of fire according to the type of satellite from 2001 to 2019. To assess the destructive power of the observed fires and as suggested by (Giglio et al., 2006) active fires were divided into 4 categories, according to their radiative power: very low (PR< 15 MW), low (PR: 15 MW–40 MW), moderate (PR: 40 MW–80 MW), strong (80 MW–600 MW). The analysis of the seasonality of fires in a year was carried out using the Package Vegan version 1.6.5 in *R*. The matrix distance was generated with the Vegdist function using the bray Curtis index.

Results obtained from hierarchical classification were analyzed by *G* statistics of Getis-Ord a spatial autocorrelation method that enables the recognition and understanding of hot and cold spots (Getis and Ord, 1992) areas where there is a statistically lower or higher concentration of forest fires. These are defined through statistics such as the standard deviation (*Z* score) and probability values (*p*), where high values of *Z* score associated with low values of *p* constitute a hotspot or cluster zone (Manuel and PompaGarcía, 2018). The *G* statistic was applied with the hotspot analysis tool of ArcGis 10.4.1.

The spatiotemporal clustering of fire occurrence were derived from maps of fire density for all fire seasons from 2001 to 2019. The maps describe fire counts per unit area, and allow the distinguishing of hotspots (with high fire occurrence density) and cold spots (with low fire-occurrence density) (Müller and Suess, 2011). The non-parametric Kernel density estimation (Diggle, 1985) with a fixed bandwidth of 4 km was used to produce continuous fire intensity surfaces from the active fire data. KDE has been widely used for hotspot analysis and detection. The objective of KDE is to produce a smooth density surface of point events over space by computing event intensity as density estimation (Serra-Sogas et al., 2009)

After running a preliminary analysis of Kernel density a spatial *K*-function of Ripley was calculated to assess possible spatial clusters of fires locations. Diagnostics for spatiotemporal clustering and tests for space-time interaction were computed using the splancs package adapted for use in *R* (Rowlingson and Diggle, 1993; Ceyhan et al., 2013).

For the validation of the results obtained by remote sensing, field verification of fire alerts was performed. During the internship, the registration to the fire alert system allowed to collect and identify directly on the field 25 active fires points.

Results

Temporal organization of recorded fires

Temporal changes of fire frequency for the whole area were investigated on a yearly, monthly and daily basis from 2001-2019. Monthly changes were studied for each year. A total of 4602 fires with a confidence value > 30% was recorded in and around Luki BR from 2001 to 2019. The distribution of fires for the different years is not homogeneous (Fig. 2). The year 2013 recorded the highest number of fires: 442 fires representing 9.61% followed by 2008 with 347 fires (7.54%) and 2006 with 321 fires (6.98%). The year 2001 was the least active with only 33 fires (0.72%) followed by 2002 (2.78%). As shown in the Fig. 3, there was a large inter-annual variation in average monthly patterns of

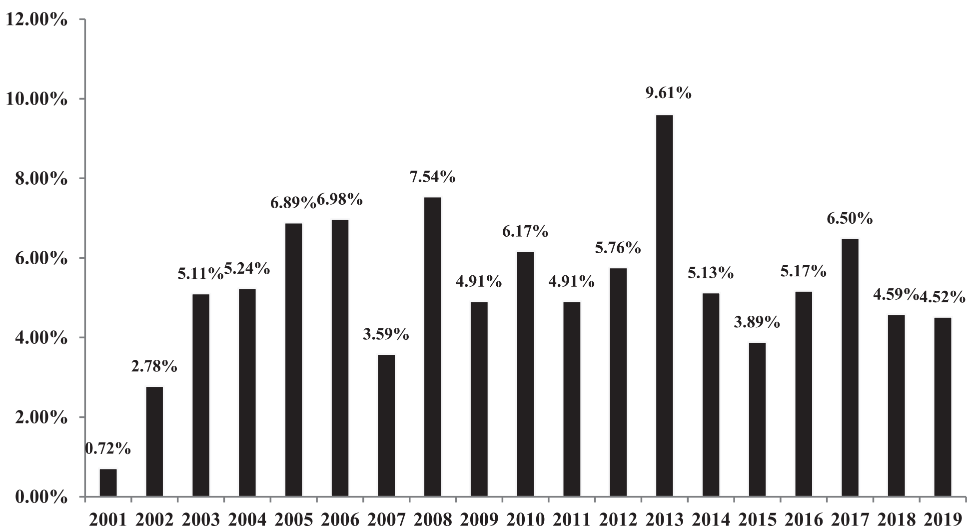

Fig. 2. Annually distribution of fires.

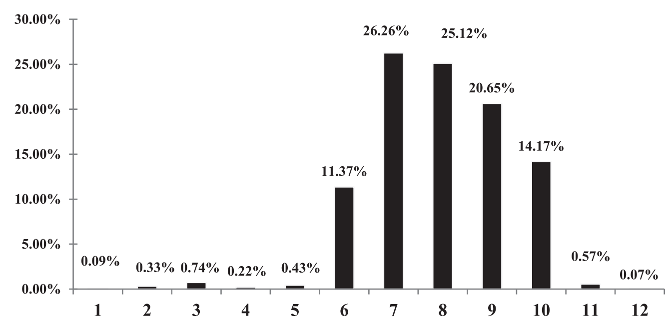

Fig. 3. Monthly distribution of fires.

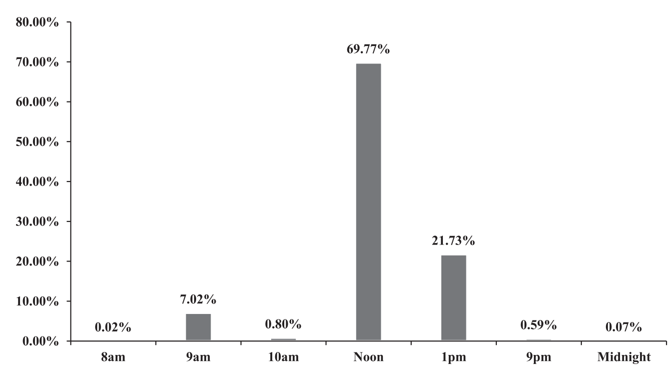

Fig. 4. . Daily distribution of fires.

fire occurrence. The most significant being July, which had the highest number of fires 26.26% followed by August (24.12%) and September (20.65%). For all years combined, a total of 97.57% of fire occurred from June to October corresponding to the dry season, January and December (the wettest months) are less active in fires with only 0.09% of fires each. This would be because in dry season, the weather is warmer and drier, which favors the occurrence of fires and their spread.

The daily repartition of fire is far from random (Fig. 4). Approximately 69.77% of the fires take place at Noon (12 pm) and 21.73% at 1 pm. Only a small number of fires appear in the morning and fires are almost absent during the evening hours. This would be because from 12 o'clock onwards, the weather is warmer and drier, which favors the occurrence of fires and their spread.

Spatial clustering analysis of fires

The first step was to perform data analysis to visually inspect the point (Fig. 5**A**). The result obtained allowed the generation of a Kernel density map (Fig. 5**B**). The Kernel density map does not take into account the time effect. The results show that most of fires occurred in the southeast part of the Study Area. The northwest part of the study area appeared to be the least affected by fires. The central area of Luki BR was the only area least exposed to fires in the Study Area.

Fires radiative power

The values of Fire Radiative Power (FRP) varies from very low (RP < 15 MW) to high (80 < RP < 600 MW). And for our study area, the FRP distribution is not uniform. About 98.65% of the fires have a low PR followed by those with a very low PR (0.85%). Only 0.30% of the fires had medium RP and 0.20% had high PR (Fig. 6). The Fire Radiative Power of the recorded fires varies between 0 and 339.90 MW with the highest value in October. The mean value of the radiative power is 23.47 MW with a large value of standard deviation 24.29 MW. September has the highest average (25.9 MW) of all recorded fires followed by August (26.03 MW) and October (25.39MW). The lowest values were recorded in December (11.03 MW) and February (11.32MW) (Fig. 7).

The correlation test between months and the corresponding FRP values revealed a significant difference (*p*-value <0.00001). In order to discriminate the distribution of fire based on their radiative power and frequency according to the months of the year, a hierarchical classification has been carried out based on fire data covering 2001 to 2019 (Fig. 8). The hierarchical classification of fires during the year considering the FRP and their frequency 2 main groupings corresponding to 2 climatic seasons. The first group is made up of the dry months (from June to October 2019) and the second of the wet months (from January to May).

Based on the Fig. 8 presented above, the *G* Getis–Ord statistic was applied for the two subgroups in order to define the spatial patterns presented by the fire events (Fig. 9 (A) for subgroup 1 containing dry months and (B) for subgroup 2 corresponding with rainy months). The results obtained showed that the southeast part of the region and the southwest had the hotspots. The north part and the Luki BR are cold spot regions.

Second order analyze

The Fig. 10 below present Ripley's *K* -function for overall fires in the study site. Given that the observed values of *K* are outside the confidence interval of expected values, at very short distances (less than about 4 km

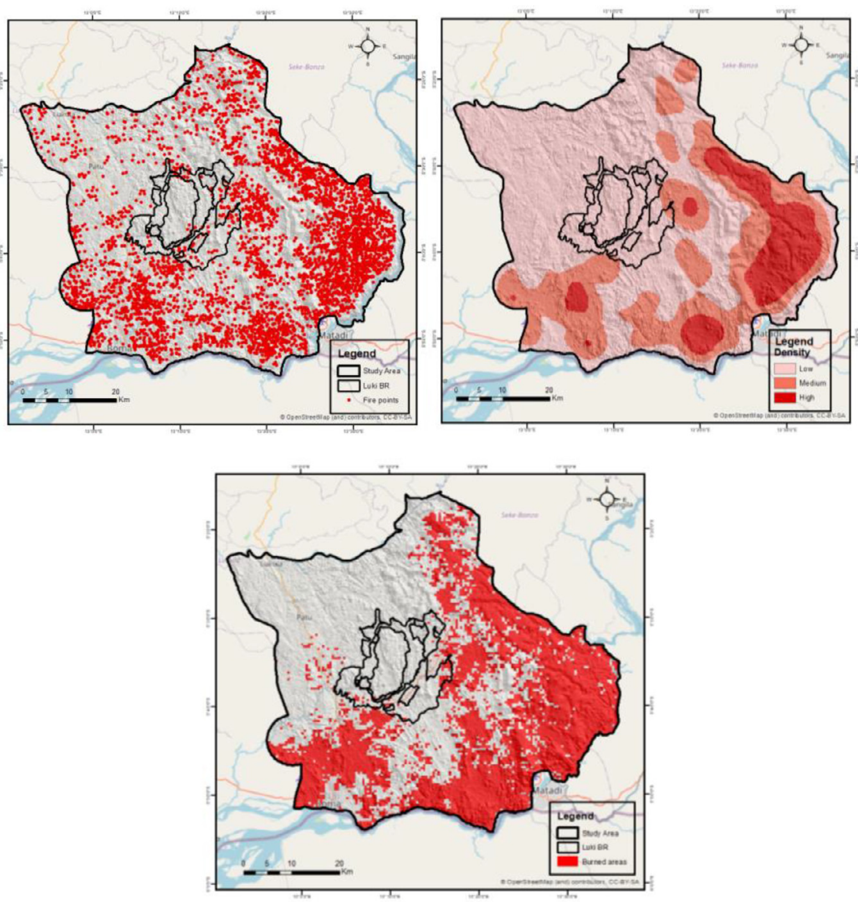

Fig. 5. Fire distribution (A), Kernel Density of fire (B) and Burned areas (C).

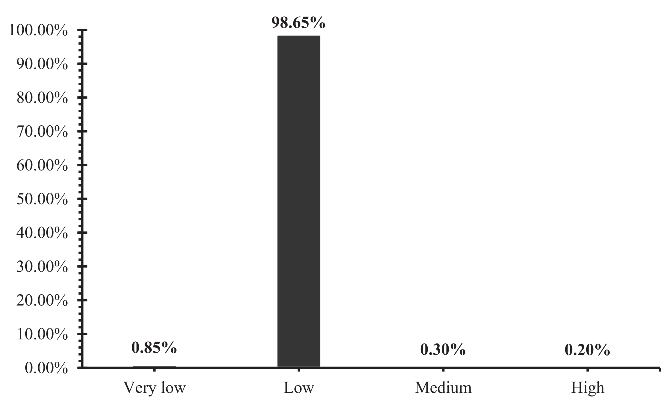

Fig. 6. Fire radiative power classes.

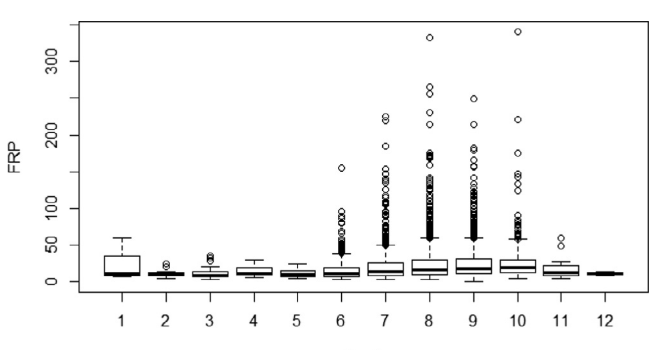

Fig. 7. Fire Radiative power (MW).

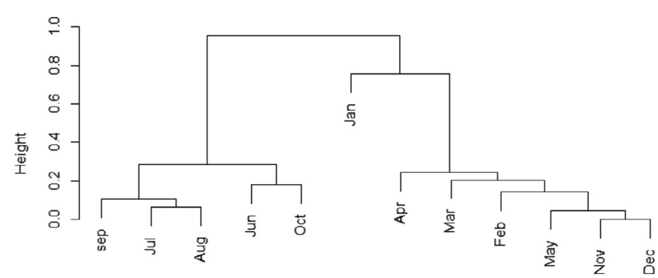

Fig. 8. Hierarchical classification of fires according to their PR.

radius) the distribution of bushfires is statistically more aggregated than a random distribution, whereas at long distances from 4 to 20 km radius the distribution of bushfires is statistically more dispersed than a random distribution (Fig. 11).

Spatio-temporal analyzes

To analyze the space-time interaction, the Monte-Carlo test was ran. Considering the year as unit of time, the result show that spatially closest bushfires are more likely to have appeared at short time intervals (*p-value*= 0.012).

The two plots are the standardized residuals against the product of the spatial and temporal *K*-functions (left) and histogram of the test statistics (right), where the statistic for the data is indicated with a vertical line.

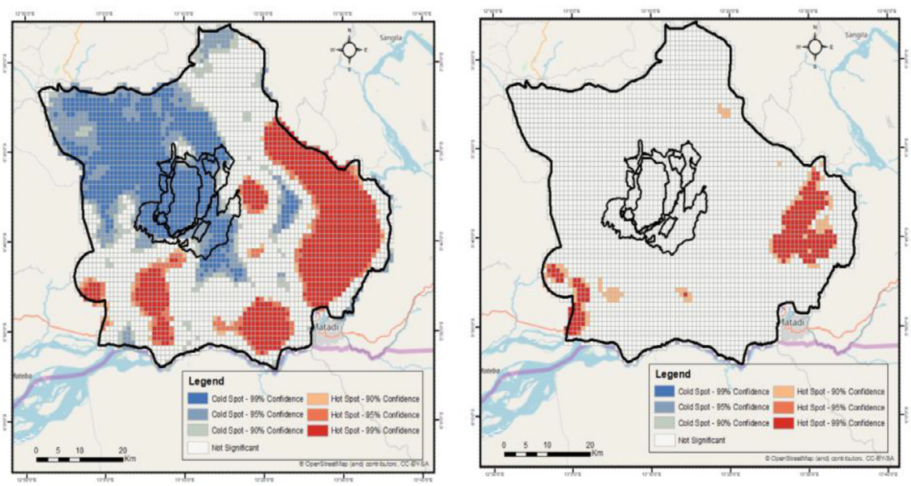

Fig. 9. G Getis-Ord statistic of fire occurrence in dry months (A) and rainy months (B).

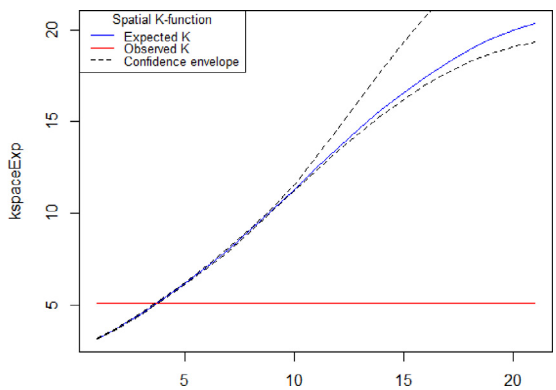

Fig. 10. Second-order analysis of fire locations (Ripley's *K*-Function).

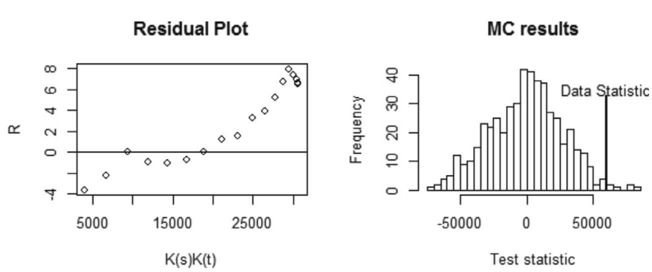

Fig. 11. Diagnostic plots for space-time clustering based on months.

Discussion

Several studies have been conducted to assess the forest fire risk using MODIS near real time hotspots for better forest management. In order to obtain a proven fire base ignoring misalerts, fire points with a confidence < 30% were excluded. The advantage of this exclusion has been demonstrated by (Caillault et al., 2010) and (Giglio et al., 2018). For the fire risk assessment, the kernel density analysis (KDE) and Gi* hotspot methods were used. They are used jointly to determine the clusters and statistical significance of point patterns (Ahola et al., 2007; Krisp et al., 2005). Their use made possible the identification of areas where a high number of fires are recorded and which require spatial attention. The space-time interaction analyzed trough the Monte Carlo test showed the interaction of fire events over the study area.

The evolution of fires over time showed that 2013 was the most active year. This high frequency can be partly explained by the year's weather conditions. The year 2013 was among the years with the longest dry season. On the other hand, the opposite situation is observed for the year 2001, which recorded the fewest fires over the studied period. This situation can be linked to the fact that Aqua satellite, which recorded the highest number of fires in our zone, cycles in the afternoons when the greatest number of fires in the area takes place, was only functional from May 2002 (Elias and Didier, 2019; Giglio et al., 2006, 2018). Some fires that took place that year were therefore not recorded. Annual variations in fire frequencies over the months depend on local climate and human activities. Indeed, in and around Luki BR, the months with higher fire frequencies correspond to dry months. During the dry season, rainfall becomes scarce, the desiccation of vegetation and soils as well as wind shifts are favorable to the origin and spread of fires (Colin et al., 2001). Our results corroborate those found by (Giglio et al., 2003), indicating that the number of months of wildfires is 2 to 6 per year in the tropics. Lutete et al. (2016) found that bush fires in the selected four protected areas of DR Congo is closely linked to climatic seasons especially in the dry season, which recorded highest proportion of fires. These same results were confirmed by community surveys, which also stated that almost all fires occur during the dry season. The low frequency of fires during the rainy season is explained by the coolness of the vegetation and the weather conditions (frequent rainfall, high atmospheric humidity, low temperature) that are unfavorable to the emergence and spread of fires. The fires that take place during the dry season are of two origins: they are either due to the burning of the savannas (more frequent activities from June to August) or to the pre-cultural work that takes place from September until the beginning of the agricultural season in October. The fires detected during the last two months are therefore linked to the conquest of new land being cleared by fire (Elias and Didier, 2019). During these activities, fallow land is cultivated and new land is cleared. In both cases fire is used to facilitate agricultural activities. Investigations have shown that the largest proportion of the population uses fire in their field preparation work. These results confirm the results found by other researchers on the use of fire for agricultural work. Semeki et al. (2018) in their study carried out in the Mondo Missa Hunting Domain in northern DR Congo stated that slash-and-burn agriculture is the main activity for the survival of local populations. This system is characterized by partial clearing (some trees are conserved) of primary forest in the dry season and the cleared areas are then burned before proceeding with field preparation and sowing. In and around Luki BR, the cleared leaves are piled up in piles and burnt at the end of the work around noon and 1 pm explaining the high number of fires at these times of the day. In fact, our results showed that almost all of the fires occur between noon and 1 pm and are more frequently recorded by the Aqua satellite. As described above, fire occurs at the hours of passage of the Aqua satellite (Müller and Suess, 2011), which consequently records the greatest number of fires. Giglio et al. (2006) found that the detection rates of

Aqua tend to be greater in the tropics because the overpass at approximately 1:30 pm occurs at a time close to that of the peak fire activity. Elias and Didier (2019) in their study on fire in Burundi made a different observation. Fires occur in Burundi before noon and are recorded by Terra satellite, which crosses the equator at 10:30 am on its way up and 10:30 pm on its way down, records the highest number of fires. Indeed, results obtained during the surveys have shown that the choice of these burning hours is dictated by the climatic conditions at these specific times, which are favorable for successful burning. These hours are characterized by a strong sunshine facilitating the drying of the morning dew as well as the presence of the wind facilitating the propagation of the fire.

The assessment of the fire power is based on its radiative power (Giglio et al., 2006; Colin et al., 2001). In the study area, 4 of the 5 classes of PRs were recorded. The range vary from very low RPs to high RPs (Giglio et al., 2006) and the mean of RPs for the recorded fires was in range of fire PRs around the equator, which is 35 MW (Giglio et al. 2006). The most represented fires are those with very low to low RPs. Very low FRP correspond to dense forest fires or agricultural use fires, where controlled fires are small. In the tropics, fires with low PR are associated with grassy formations (Giglio et al., 2006), which is frequent in fallow and uncleared land. Moderate, strong and very strong fires are poorly represented, but very destructive. The hierarchical classification of fire based on the PR clearly distinguishes between dry season and rainy season fires. These results were also found in Loas (Müller et al., 2013) where fire occurrences are strongly clustered in the dry season.

The spatial distribution of fire indicates that the southeast regions were most affected by fires and less in the northwest and northeast parts. This is explained by the type of vegetation cover. Indeed, the south-western part is dominated by savannah, unlike the northern part in which the Luki BR is located and which is mostly forested. The studies conducted by (Cochrane, 2003; Langner and Siegert, 2009) provide enough evidence that the probability of occurrence and spread as well as the detection of a fire in undisturbed dense forest and the detection of a possible fire in such forests is low because of the dense canopy. The results of the Kernel Density indicate the same trends.

Conclusion

This study presents information for Fire management in and around Luki Biosphere Reserve. 4602 fires events were recorded and 150132 ha burned from 2001 to 2019. As the fire season extent from June to September, measures must be taken during this period of the year. The spatial distribution of the fires indicates the areas for which special attention should be directed. Fires that are close in time are also close in space, indicating the importance of preventive action to avoid the spread of fire over large areas. The results of this study will help managers of this protected area to take special actions for fire management. The intervention may be centered at 3 levels: *before*, for prevention and control, *during,* to detect and monitor fire movement and *after,* for fire footprint mapping and assessment of burnt areas. It is important to set up fire brigades, especially during the critical period when fire activity is intense.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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