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Characterisation of spatial and temporal distribution of the fire regime in Niassa National Reserve, northern Mozambique

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Abstract. The Niassa National Reserve (NNR) is the largest conservation area of the Miombo woodlands in southern Africa, representing one of the most remote and pristine biodiversity spots. Anthropogenic fires have long been one of the main ecological drivers in these woodlands. However, the constraint in understanding fire effects results from limited data and accessibility to existing fire records. This study is intended to contribute to the understanding of fire ecology in these woodlands by assessing the fire regime in NNR. We used the moderate resolution imaging spectroradiometer (MODIS) daily active fire (MDC14ML) and burned-area (MCD45A1) products to characterise the fire regime in terms of seasonality, intensity, density, burned area, frequency and mean return interval for the period from 2000 to 2012. The results indicated that fire activity starts *c*. April and peaks in the late dry season (August–October). Approximately 45% of the area burns every year, especially the north-central and eastern sectors, with fire intensity displaying an inverse relationship with frequency. In conclusion, our study demonstrates the relevance of remote sensing for describing the spatial and temporal patterns of fire occurrence in the Miombo eco-region and highlights the necessity for controlling fire and managing fuels in this important conservation area.

Additional keywords: fire density, fire frequency, Miombo woodlands, MODIS active fire, MODIS burned area.

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Introduction

Anthropogenic fires are among the main drivers of the southern African Miombo woodlands. They are, together with climate, herbivory and other human activities (agriculture, logging, charcoal production, etc.), key in forming the woodland structure and composition (Frost 1996; Ribeiro *et al.* 2008; Tarimo *et al.* 2015). Late dry-season fires are of sufficiently high intensity to kill the natural regeneration of main tree species such as *Brachystegia* spp. and *Julbernardia globiflora*. However, a fire-return interval of 2–4 years has been considered sufficient to allow woody vegetation to grow above the threshold where they are killed by a fire (Frost 1996; Chidumayo 1997; Ribeiro 2007). A decrease in the fire return interval may impose major changes in the ecosystem's structure and composition (Ribeiro *et al.* 2008; Tarimo *et al.* 2015).

The variability of fire regimes in African woodlands is determined by a combination of climate (precipitation and temperature), herbivory and human activities (Archibald *et al.* 2010). Herbivores influence the tree : grass ratio in the ecosystem either by browsing or grazing woody and grass species This influences the amount of fuel load, which is key in determining the occurrence of fires and their intensity. This so-called *pyric-herbivory* is still not completely understood in the Miombo ecosystems. Humans are the main initiators of fires through activities such as honey gathering, agriculture and hunting, among others, which use fires as a readily accessible management tool. Human population growth has amplified the influence of people on fire regimes, resulting in human drivers being more important than climate and herbivory. Thus, human drivers will continue to regulate future fire regimes under changing climate conditions (Trapnell 1959; Kikula 1986; Scholes and Walker 1993; Frost 1996; Chidumayo 1997; Ribeiro *et al.* 2015).

African savanna fires play a key role in atmospheric chemistry and global climate as they are responsible for approximately

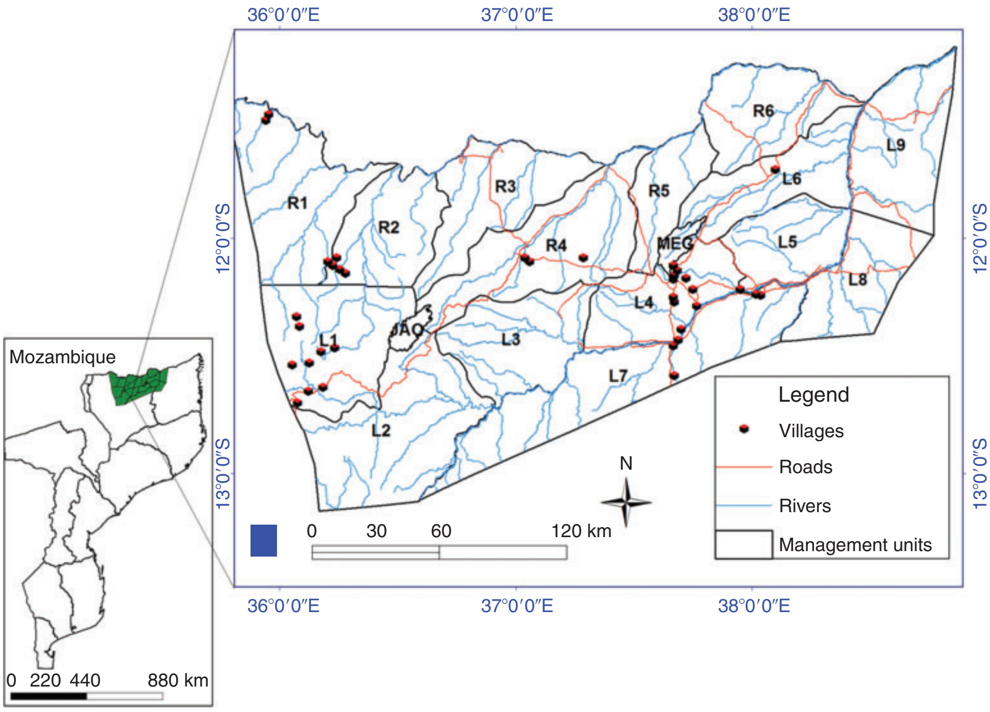

Fig. 1. Niassa National Reserve geographic location in northern Mozambique.

two-thirds of the biomass burned and account for approximately one-third of the total global emissions of trace gases and aerosols (Crutzen and Andreae 1990; Andreae 1991; Hao and Liu 1994; Swap *et al.* 1996; Scholes and Andreae 2000; Andreae and Merlet 2001; Hély *et al.* 2003; Sinha *et al.* 2004). In the context of global climate changes and human growth, anthropogenic fires may become more intense and frequent, thus increasing the continent's contribution to greenhouse gas (GHG) emissions.

Fire in southern Africa has been a controversial topic. It is often labelled a harmful phenomenon to terrestrial ecosystems, but at the same time it is an important management tool. Since complete exclusion of fires in the region is probably unattainable, there has been a gradual change in the perception of fire from being an undesirable and destructive disturbance to a natural and essential element of natural resources management (Saket 1999).

A key challenge in addressing fire regimes in Miombo woodlands is the lack of complete and consistent fire records (Tarimo *et al.* 2015). Fire records are limited to a few isolated areas in which fire management plans are implemented. Kruger National Park in South Africa has the longest history of fire records in the region, but none is reported for Miombo woodlands. In the absence of systematic long-term fire records, satellite data form a unique source of fire information (Archibald *et al.* 2010; Giglio 2010; Stellmes *et al.* 2013; Tarimo *et al.* 2015). Datasets on active fires and burned areas derived from the track-scanning radiometer (ATSR), SPOT-VEGETATION and moderate resolution imaging spectroradiometer (MODIS), among other satellite sensors, are available in the public domain. They provide fire patterns at a medium-scale spatial resolution and at a very short temporal coverage. Landsat data have been shown to be relevant to address fire regimes given its medium resolution. However, the low temporal resolution may limit studies on fire regimes, in which fire frequency, intensity and seasonality need to be investigated.

This study is a result of a 13-year research program (2004–2017) in the Niassa National Reserve (NNR) in northern Mozambique (Fig. 1), one of the most important conservation areas of Miombo woodlands in the country and worldwide. The program has resulted in a comprehensive understanding of the effects of fires on the ecosystem (Ribeiro *et al.* 2008, 2009, 2013, 2015; Maquia *et al.* 2013). Several studies in the region reveal that fire frequency (number of fires per unit of time) and intensity (energy released during a fire) are key components of the fire regimes that influence vegetation (Trapnell 1959; Barnes 1965; Ryan and Williams 2011). A fire frequency of 2–4 years allows the woodland to recover after a fire and promotes the germination of some species (Frost 1996) but no fire intensity patterns were described for the woodlands. The present work constitutes the first multi-year study of the spatial and temporal patterns of fire in NNR aimed at contributing to refining the fire management plan for the area. Our specific objectives are to (1) determine the spatial distribution of fire frequency; (2) investigate the relationship between the fire frequency, density and intensity of burnings; and (3) evaluate the intra and inter-annual variations of fire occurrence.

Materials and methods

Study area description

NNR is located in northern Mozambique between parallels 12°38′48.67″S and 11°27′05.83″S and the meridians

36°25′21.16″E and 38°30′23.74″E (WWF SARPO 2002*a*, 2002*b*). With a total area of 42 000 km^2 (Fig. 1; SGDRN 2010) it is considered the largest conservation area of Miombo in Mozambique (36% of the total national protected area).

The climate is tropical sub-humid with a mean annual precipitation (MAP) of 900 mm that increases from the east (800 mm) to the west (1200 mm) and a mean annual temperature (MAT) of 25°C during the dry season (May–October) and 30°C during the wet season (November–April). The reserve has a gently undulating landscape on a plateau with an elevation ranging from 300 to 600 m above sea level (ASL) and two main peaks, Jao Mountain in the west (1200 m ASL) and Mecula Mountain in the east (2000 m ASL).

Miombo woodlands cover more than 70% of the total area of the reserve and are composed of more than 800 plant species, half of which are endemic. *Julbernardia globiflora* Benth. (Troupin), *Brachystegia* spp., *Dyplorhynchus condilocarpon* (Müll. Arg.) Pichon, and *Pseudolachnostylis maprouneifolia* Pax, among other tree species dominate the canopy cover in this area (Ribeiro *et al.* 2008; Ribeiro *et al.* 2013), and a dense and continuous grass layer dominates the forest floor. NNR has also a high diversity of faunal species which includes elephants, palapala, lions, wild dogs, leopards, buffalo and more than 400 bird species (Craig 2009; SGDRN 2010).

The human population inside the reserve is estimated at 45 000 inhabitants (SGDRN 2010). These are distributed among 50 villages, particularly in the settlements of Mecula (Mecula District) and Mavago (Mavago District). The human density is considered low (0.8 inhabitants km^{-2} in Mecula and 1.9 inhabitants km^{-2} in Mavago) compared with other places in the country. The main human activities in this area include subsistence agriculture and hunting, honey gathering and commercial trade with Tanzania. Fire is the cheapest and readily accessible management tool for most of those activities (Ribeiro *et al.* 2008, 2009; 2013, 2015).

Datasets and preprocessing

In this study, we used two MODIS datasets, namely, the daily active fire product (Level-5 gridded 1000-m MDC14ML) and the monthly burned-area product (Level-3 gridded 500-m MCD45A1). The datasets were obtained for the period between November 2000 and December 2012 from freely available sites at http://fuoco.geog.umd.edu and http:/ba1.geog.umd.edu (Justice *et al.* 1998; Giglio *et al.* 2000; Justice *et al.* 2002). According to Giglio (2010) MODIS data before November 2000 are considered untrustworthy because of frequent detector outages.

MCD14ML provides, among other things, the coordinates of detected fires (the centre of fire pixels at 1-km resolution), their acquisition dates and times, and the respective fire radiative power (FRP). MCD45A1 detects the approximate dates of burning and maps the spatial extent of monthly fires. A detailed description of these products can be found in Pereira (2003); C Justice, L Giglio, L Boschetti, D Roy, I Csiszar, J Morisette and Y Kaufman (unpubl. data); and Davies *et al.* (2009).

All images were georeferenced to an already corrected Landsat ETM+ image in UTM projection (zone 37S, datum WGS84) by image-to-image registration at $\leq$0.5 root mean square error (RSME) using 20 control points that corresponded to rivers and streams bifurcations and other identifiable features at all resolutions. Corrected images were mosaicked and subset by using appropriate tools in Earth Resources Data Analysis System (ERDAS) to incorporate only the spatial extent of the NNR.

Spatial and temporal analysis of burned areas and active fires

This study used a combination of methods to capture the temporal and spatial characteristics of the fire regime. This methodological approach was an adaptation of previous work developed by Smith and Wooster (2005), Archibald *et al.* (2010) and Stellmes *et al.* (2013).

The fire regime was described by six descriptors: (1) Fire density; (2) fire intensity; 3) (fire seasonality; (4) burned area; (5) mean fire return interval (MFRI); and (6) fire frequency.

Fire density

Daily nominal and high confidence (>80%) active fires were extracted from MCD14ML in ArcGIS, ver. 9.1 (ESRI, Redlands, California, USA). Low-confidence pixels were not used to avoid errors resulting from false-alarm detections. The active fire counts were converted to the number of fires per square kilometre by using the kernel density function in ArcGIS, ver. 9.1.

Fire intensity

On a daily basis, the maximum fire radiative power (FRP) of fires detected by MODIS MCD14ML with a high confidence level (>80%) was recorded. This is measured in units of megawatts per pixel (MW $pixel^{-1}$; Archibald *et al.* 2010). The sum of the FRP per fire pixel in a year (Kaufman *et al.* 1996) was used as an aggregation criterion. To compile the FRP for the entire study area, we calculated the sum of FRP for the entire period and extracted it for each fire frequency and fire density category.

Burned area

To produce the annual map of burned areas, we summarised the monthly burned area data extracted from the MCD45A1 products. All pixels in the MCD45A1 with a nominal value between 1 and 366 (Julian days) were classified as area burned per year and the respective dates were recorded (Roy *et al.* 2008). The total area burned (km^2) was calculated by using the utilities tool in ArcGIS, ver. 9.1. We used only pixels with confidence levels 1 and 2 (derived from the Quality Assurance layer), which represent the most confident detections. We also excluded invalid pixels (water, clouds, snow, aerosols, no or not enough data to perform the BRDF inversion) from the dataset (Archibald *et al.* 2010; Stellmes *et al.* 2013).

Fire seasonality

To explore the intra-annual variations of the burned area, the year was divided into three seasons, namely, wet (November–April), early dry (May–July) and late dry (August–October) according to the annual pattern of rainfall distribution. The average and standard deviation in area burned each month and the active fires were extracted for each period to address fire dynamics throughout the year.

Fire frequency

Monthly burned area layers were combined to calculate the number of times a particular pixel burned during the 12-year period (Archibald *et al.* 2010; Stellmes *et al.* 2013). Fires in Miombo are mostly grass- or litter-fuelled, with average return periods of 3–4 years (Frost 1996), thus the 12-year MODIS dataset can capture the variation in fire frequency in this area.

Mean fire return interval (MFRI)

The expected return time of fire to a particular area or the average number of years between two consecutive fire events at a particular site were calculated according to Ribeiro (2007), using Eqn 1:

$$\mathrm{MFRI} = \mathrm{T} \times (\mathrm{A} \div a) \qquad (1)$$

where T is the period of study (12 years), A is the total area under study (42 000 km^2) and a is the total area burned (calculated as the sum of active fires and burned areas) during the period of study.

FRI mapping

To understand the spatial distribution of the FRI a raster of 30-m pixel size was produced for each year in ARCGIS, ver. 9.1. The yearly maps corresponding to the total area burned were reclassified to produce an image with two gridcodes (one for burned pixels and zero for unburned ones). The yearly rasters were added to create a composite map of fire frequency and the final FRI map was obtained by using the *raster calculator* tool in ARCGIS, ver. 9.1, to calculate the number of times a fire returned to a pixel during the period. This map had 12 frequency gridcodes corresponding to the number of times a fire returned to a pixel in 12 years. For example, a gridcode of one corresponds to areas burned every year, whereas a gridcode of 12 indicates areas burned once during the period of study.

To validate the fire frequency map we conducted an accuracy assessment analysis according to Congalton and Kass (2009). In total, 108 circular sample plots (diameter 30 m) were collected for high-fire frequency pixels (burned 11–12 times during the period) and low fire frequency (burned 1–2 times during the period). Each selected pixel was sampled and evidence of burning (trees scratched, killed, grasses burned, impermeable soil layer) and assessments of the vegetation structure and composition were performed following ecological methods recommended by Kent (2012). This process does allow for an indirect accuracy assessment as places with high fire frequency presented a different vegetation structure and composition as reported by Ribeiro *et al.* (2008). Consultations with local people were done to obtain information about the history of fire in the area and that was recorded as a nominal variable. The overall accuracy was calculated by using the error matrix method as suggested by Olofsson *et al.* (2014). The matrix is a simple cross-tabulation of the class labels allocated by the classification of the remotely sensed data against the reference data for the sample sites.

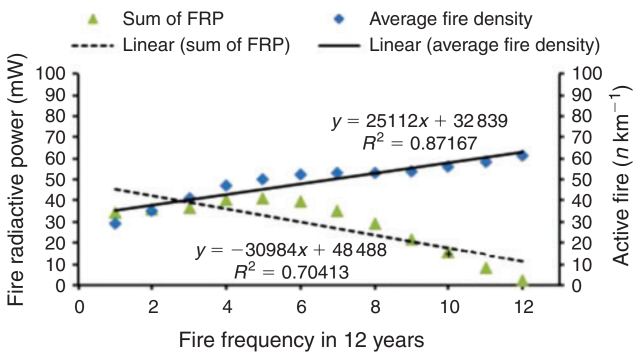

Fig. 2. Relationships between fire density, intensity (sum of FRP) and frequency in the Niassa National Reserve.

To address the relationships between the mean annual fire intensity, mean annual fire density and fire frequency, we conducted a linear regression analysis at the 95% confidence interval, considering fire frequency as the predictor (independent variable). This analysis was aimed at investigating whether high fire frequency produces denser and stronger fires, which can be considered a priority for fire management. Checks were performed to ensure that the two statistical assumptions of normality of residuals and homogeneity of variances were not violated.

Results

Relationships between fire intensity, density and frequency

The mean fire density in this area varied between ~40 and 70 fires km^{-2}, with a positive and statistically significant relationship with fire frequency ($R^2 = 0.87$; $P < 0.05$; Fig. 2). For low fire frequency, the density of fire was ~40 fires km^{-2}, whereas high fire frequency resulted in an increased density of 70 fires km^{-2} (Fig. 2).

Fire intensity had a statistically significant inverse relationship with fire frequency ($R^2 = 0.704$; $P < 0.05$). Low fire frequency produced fires of high intensity (80 MW), whereas high fire frequency resulted in low intensity fires (less than 40 MW; Fig. 2).

Intra- and inter-annual variations in active fires and burned areas

Fire seasonality in NNR followed the annual rainfall distribution, peaking in late dry season (August–October) for all years (Fig. 3). During the 12-year period, there was a tendency for an increase in both active fires and burned area between 2001 and 2008, when ~34% of the entire NNR burned. Burned area also peaked in 2001 (42% of the entire NNR), 2006 (28%), 2007 (27%) and in 2010 (29% of the total area). After 2008, there was a slight decrease in the number of active fires, whereas the burned area showed a quasi-biannual cycle.

Mean fire return interval (MFRI) and fire frequency

The MFRI indicates that fire returned to a particular site every 3.29 years, which means a total fire frequency of 0.36 $year^{-1}$. The spatial distribution of the MFRI reveals that the area did not

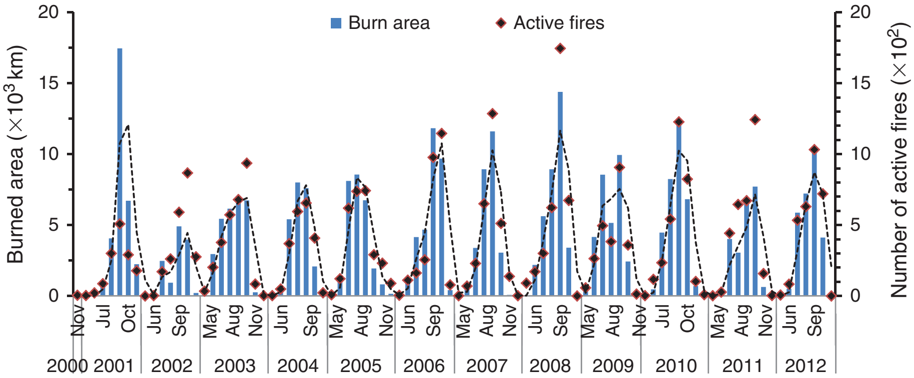

Fig. 3. Area burned per season between November 2000 and December 2012 in Niassa National Reserve.

burn uniformly, and the MFRI in eastern and north-central NNR was as low as 1 year (i.e. annual burns) and a few places burned twice or three times a year (Fig. 4).

During the 12-year period, 45% of the reserve burned annually or every other year, 27% burned every three to four years and only 9% of the whole area did not burn during the study period. This corresponds to the tops of the mountains (Mecula and Jao) and along the main rivers, where human activity is absent or evergreen moist forest is dominant.

MODIS products provided 88.9% overall accuracy, which is a very good agreement between the mapping exercise and what was actually found on the ground. We obtained 88.2% user accuracy in detecting burned areas, i.e. only 11% of all burned pixels were wrongly classified as unburned (Table 1). This is considered satisfactory given the spatial resolution of the MODIS burned-area product of 500 m.

Discussion

The remote sensing-based approach used in this study to characterise the fire regime in NNR proved to be sufficiently accurate to inform decision-making (i.e. the NNR management team) regarding fire management in this important conservation area. This was the first study to compile spatial and temporal (12 years) distributions of fires in NNR agreeing with patterns reported elsewhere in southern Africa (Trollope 1978; Frost and Robertson 1985; Chidumayo 1997; Van Wilgen *et al.* 2004; Ribeiro 2007; Archibald *et al.* 2010; Stellmes *et al.* 2013; Tarimo *et al.* 2015).

The inverse relationship between fire intensity and frequency is interesting and brings up key questions for fire management. Several authors (Bloesch 1999; Van Wilgen *et al.* 2004; Govender *et al.* 2006) reported that in African savannas, grass biomass (the major component of the fuel load), fuel moisture content and weather conditions during burns influence the fire regimes including their frequency and intensity. Ribeiro *et al.* (2009) reported that fire frequency in NNR is significantly predicted by the vegetation and elephant densities, followed by mean annual precipitation. In a follow up study, Cangela (2014) found that temperature is also important, whereas human density was associated with reduced fire frequency (also supported by Archibald *et al.* 2010). In general, elephants remove woody vegetation, thus promoting fuel load, which in a situation of reduced moisture and high temperature (typical of the late dry season weather conditions) increases the likelihood of intense fires. However, the effect of fire should not be decoupled from herbivory activity (Fuhlendorf *et al.* 2009). This so called *pyric-herbivory* interaction explains positive and negative feedbacks between the two factors. One of such feedbacks is that grazers are attracted by post-fire regrowth due to elevated grass nutritional value, which depending on the grazing intensity, may keep grass biomass short, reducing fire occurrence in the next season (Govender *et al.* 2006; Archibald *et al.* 2010). Our study did not sufficiently explore these relationships, thus our results are insufficient to recommend management practices. These issues will be further explored as part of the ongoing research program.

The MFRI of 3.29 (decreasing to MFRI = 1–2 in the north-central and eastern zones) is similar to the patterns found in the region. Chidumayo (1997) recorded a MFRI of 1.6 years in the Zambian Miombo woodland over a four-year period, whereas Frost (1996) observed a regional MFRI of 3 years. Recently, Tarimo *et al.* (2015) studying the fire regime in Miombo woodlands in Tanzania detected a MFRI of 2.7 years. However, the fact that the area did not burn uniformly reveals that the average MFRI must be interpreted together with its spatial distribution if correct management decisions are to be made.

The observed spatial and temporal distributions of fire may be responsible, among other things, for a varied vegetation structure and composition from the north-central and eastern sections to the west. In fact, previous findings for Miombo woodlands and for NNR in particular indicated several compositional and structural differences associated with MFRI (Bond and van Wilgen 1996; Ribeiro *et al.* 2008). For instance, although the typical Miombo species (*Julbernardia globliflora* and *Brachystegia* spp.) are uniformly distributed over the reserve, tree species with higher fire tolerance, such as those belonging to the family Combretaceae (Trapnell 1959; Barnes 1965; Frost 1996), tend to co-dominate in the north-central and eastern NNR and the grass biomass is higher. In contrast, in the western sector (lower MFRI), an association with the genus *Uapaca* was observed and the grass component was reduced (Ribeiro *et al.* 2008). These observations agree with the model proposed by Higgins *et al.* (2000), in which grass–tree

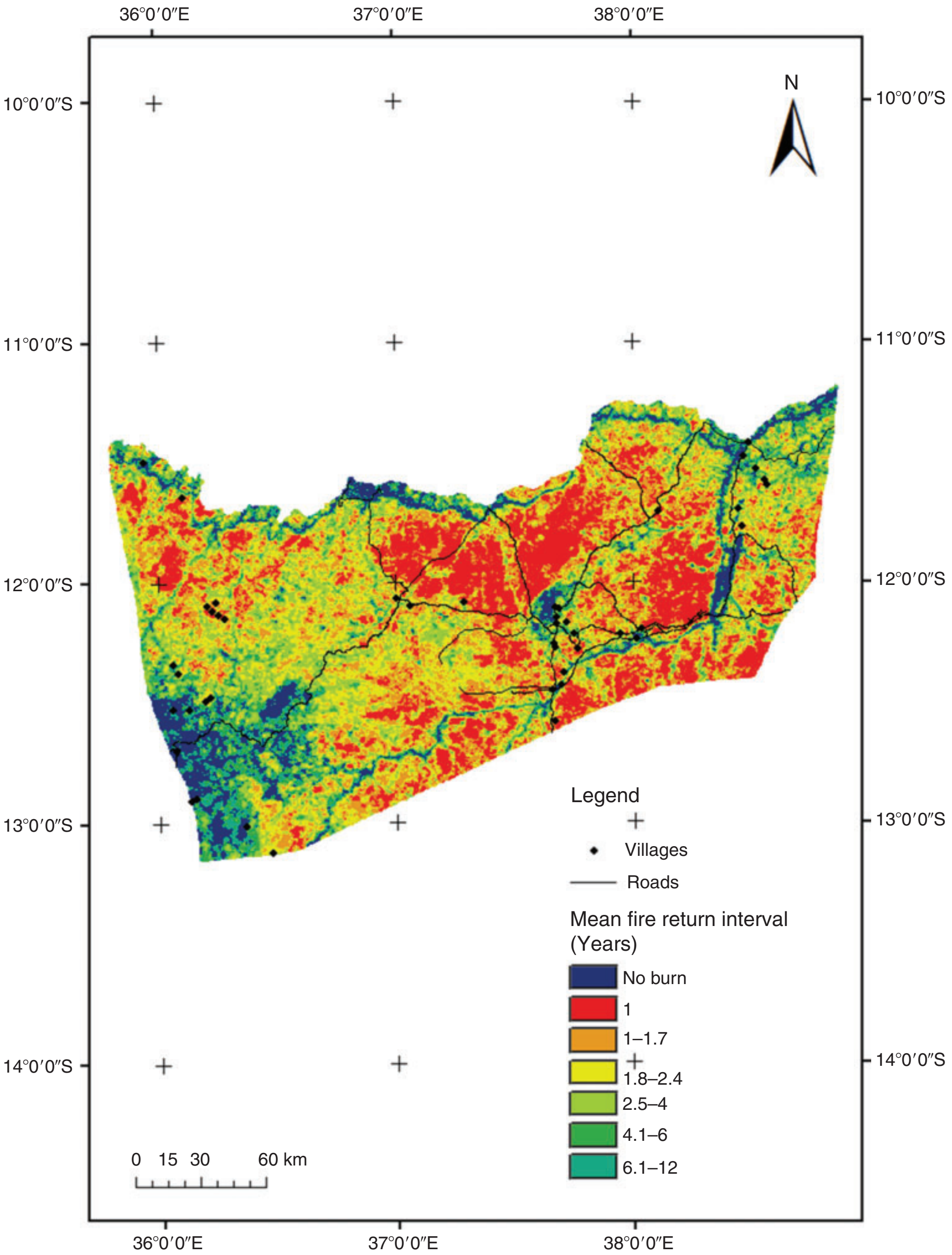

Fig. 4. Fire Return Interval (FRI) in Niassa National Reserve; the north-central and eastern sectors burned more frequently (FRI = 1–2 years) than most of the west side (FRI >2 years).

Table 1. Error matrix for validation of the fire frequency map

		Validation Categories		Total	Producer's accuracy (%)	User's accuracy (%)	Overall accuracy (%)
		Unburnt	Burnt				
Mapping categories	Unburnt	92491	1039	93530	100	33.3	88.9
	Burnt	0	2692	2692	88.2	100	
Total		92491	3731	96222			

interactions were determined by the long-term effects of disturbance (fire and herbivory) on demographics. Ryan and Williams (2011) studied the fire pattern in Miombo sites in Zimbabwe and Mozambique showing that at least two years are required between successive low-intensity burns to allow the establishment and development of trees. Although spatial variation was observed within a timeframe of only 12 years, our results indicate that almost half of the woodland is ignited at a return interval that threatens the longer-term sustainability of the tree cover (<2 years).

To sustain the integrity of the Miombo woodlands in the NNR it is critical to maintain fire regimes that retain tree-grass interactions and allow equilibrium between tree cover and diversity as well as a grass stock available for herbivores. In this context, the north-central and eastern parts of the reserve should be considered as a priority for fire management. In this area, early dry season burning is recommended to reduce grass height, which remains longer in that state given the longer dry conditions (Govender *et al.* 2006). This allows trees to recover faster by releasing higher amounts of nutrients and reducing competition with grass. In places where the fire frequency is adequate to allow vegetation recovery (every 3–4 years), we propose a *laissez faire* (no interference in the existing fire regime) system, whereas in populated areas, controlled burns to avoid the accumulation of fuel load close to infrastructures and human settlements should be considered. This kind of management system has been successfully applied to several other protected areas such as Kruger National Park in South Africa (Govender *et al.* 2006) and the Kilwa District in south-eastern Tanzania in a community-based forest management area (Mariki 2016).

Conclusions

This study provided insights about the spatial and temporal distribution of fires in NNR, northern Mozambique, using remote sensing. During the study period (2000–2012), the onset of the fire season typically occurred around April, with the number of active fires peaking during the late dry season between August and October. The mean fire return interval for the NNR was 3.29 years, with shorter intervals located in the eastern and north-central NNR, and fire intensity exhibited an inverse relationship with fire frequency. Fire frequency is directly associated with fire density, revealing hidden *pyric-herbivory* relationships. From the distribution of fires in the area, we identify the north-central and east portions of NNR as priority areas for fire management. In these areas the integrated fire management plan should consider controlled early dry season fires (by burning patches with high fuel loads, usually more than 70% grass cover, with low intensity fires that are likely to self-extinguish and reduce the fuel build-up) and controlled fires afterwards (by applying controlled patch burns to prevent further fuel build-up as well as to promote the regeneration of some Miombo tree species; e.g. *Pterocarpus angolensis* DC) to reduce fuel and avoid the destruction of infrastructures and livelihoods. Continued fire monitoring as well as small-scale experimental studies are recommended to uncover the exact causes of the observed patterns, especially concerning the impact of animal grazing intensity on fire occurrence.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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