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An analysis of the recent fire regimes in the Angolan catchment of the Okavango Delta, Central Africa

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Abstract

Background: This paper presents an analysis of fire regimes in the poorly studied Angolan catchment of the Okavango Delta in Botswana. We used MODIS data to examine the frequency and seasonality of fires over 20 years (from 2000 to 2020) in three dominant vegetation types (miombo woodlands, open woodlands and grasslands, and short closed to open bushlands), and in areas where people were present, and where they were absent.

Results: The median fire return intervals for both open woodlands and grasslands and short bushlands were relatively short (1.9 and 2.2 years respectively). In miombo woodlands, fires were less frequent (median return periods of 4.5 years). Human population density had no discernible effect on the fire return intervals, but about 14% of the miombo woodlands experienced no fires over 20 years. Ongoing shifting cultivation within miombo woodlands has led to structural changes and the introduction of fire into this vegetation type where fires were rare or absent in the past. About 12% of the miombo did not burn during the period examined where people were present, whereas close to 20% of the sites remained unburnt where people were absent. This suggests that people did not change the fire return interval in any of the vegetation types studied, but that they altered the amount of the landscape that is flammable in miombo vegetation. Fires occurred between June and September, with a peak in the late dry season (August and September).

Conclusions: Historical research indicates that late dry-season fires are detrimental to miombo woodlands, and our analysis suggests that degradation in parts of the catchment has led to the introduction of fire to this previously fire-free and fire-sensitive vegetation type. Deforestation of miombo woodlands, and the consequent introduction of fire, is a cause for concern with respect to the ecological stability of the Okavango Delta. Managers should therefore aim to protect the remaining closed-canopy miombo stands from further clearing and to attempt to shift the timing of burns to the early dry season to reduce their intensity.

Keywords: Angola, Botswana, Miombo, MODIS, Remote sensing, Savanna

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Resume

Antecedentes: Este trabajo presenta un análisis de los regímenes de fuegos en la pobremente estudiada cuenca del delta del Río Okavango en Botswana. Usamos datos de MODIS para examinar la frecuencia y estacionalidad de los incendios durante 20 años (desde 2000 hasta 2020) en tres tipos vegetales dominantes (bosques de miombo, bosques abiertos de sabanas y pastizales, y arbustales bajos cerrados y abiertos), y en áreas donde había gente presente y donde ahora está ausente.

Resultados: La mediana del intervalo de retorno del fuego tanto para las sabanas, los pastizales y los arbustales bajos fue relativamente baja (1,9 y 2,2 años, respectivamente). En los bosques de miombo, los incendios fueron menos frecuentes (la mediana del intervalo de fuego fue de 4,5 años). La densidad de la población humana no tuvo un efecto discernible en los intervalos de retorno del fuego, aunque alrededor del 14% de los bosques de miombo no experimentaron incendios en los últimos 20 años. Las modificaciones en los cultivos dentro de los bosques de miombo llevó a cambios estructurales, y la introducción del fuego en este tipo de vegetación estuvo ausente o fue rara en el pasado. En las áreas donde la gente estuvo presente, alrededor del 12% del miombo no se quemó durante el período examinado, mientras que cerca del 20% de los sitios permanecieron sin quemarse en los lugares donde la gente estuvo ausente. Esto sugiere que la gente no cambió el intervalo de retorno de fuego en ninguno de los tipos de vegetación estudiados, en los que ellos mismos alteraron la superficie del paisaje inflamable en la vegetación del miombo. Los incendios ocurrieron entre junio y septiembre, con un pico de ocurrencia al final de la estación seca (agosto y septiembre).

Conclusiones: La investigación histórica indica que los incendios al final de la estación seca son perjudiciales para los bosques del miombo, y nuestro análisis sugiere que la degradación en partes de esa cuenca ha llevado a la introducción del fuego en este tipo de vegetación que era previamente libre de incendios y sensible a los efectos del fuego. La deforestación de los bosques de miombo, y la consecuente introducción del fuego, es una causa de preocupación para la estabilidad ecológica del delta del Okavango. Los gestores deberían por lo tanto ayudar a proteger los remanentes de los doses cerrados de bosques de miombo de futuros aclareos, y hacer el intento de cambiar el período de quema hacia el inicio de la estación seca para reducir su intensidad.

Background

The ecological and hydrological functioning of the Okavango Delta in Botswana is significantly influenced by disturbances in its catchment in the neighboring country of Angola. The Okavango Delta is a key tourism destination in Botswana, as it is a unique ecosystem endowed with abundant wildlife. The Delta has been designated as a World Heritage Site by UNESCO in recognition of its outstanding environmental features. The Delta is dependent on rainfall in the highlands of central Angola, from where water flows via the Cuito and Cubango rivers into the Okavango. Angola is home to diverse ecosystems (Huntley et al. 2019), but these have not been extensively studied. The almost total lack of ecological and environmental data for the catchment is due to almost three decades of war between 1975 and 2002 that essentially prevented any scientific exploration or study (Huntley 2017). Growing concern over the threat of environmental degradation in the Angolan catchment of the Delta, and the potential consequences for its conservation, led to the establishment of the National Geographic Okavango Wilderness Project (NGOWP, Quammen 2017), which aims to establish a network of new protected areas to conserve the Delta and its Angolan catchment. The

NGOWP has funded numerous surveys to document the biodiversity, ecology and socio-economic environment of the catchment (see, for example, Goyder et al. 2018; Taylor et al. 2018; Barber-James and Ferreira 2019; Skelton 2019). The results of these and other studies are intended to provide a scientific foundation to inform the establishment of a system of protected areas in the upper catchment of the Okavango.

Fire is an important process that can influence the structure and functioning of ecosystems and impact on their conservation value. Fires are possible in African savannas due to a buildup of grass fuels that are in turn dependent on the amount of rainfall in the wet season (van Wilgen et al. 2004). Fires primarily occur in the dry season when grasses are cured, and evidence suggests that the area burnt is not limited by a lack of anthropogenic or natural (lightning) ignition sources (Archibald et al. 2009). People living in savannas use fire for a range of purposes, including the clearing of agricultural fields, improving pastures, and hunting, as well as to assist in the harvesting of natural products such as caterpillars and honey (Eriksen 2007; Shaffer et al. 2010). The catchment of the Okavango Delta is subject to regular burning, as is typical of savanna woodlands across Africa (Archibald

et al. 2010). Despite this, detailed accounts of landscape-scale fire regimes in African savanna woodlands, and their effects on the vegetation and wildlife, are limited to a few well-studied ecosystems (e.g., van Wilgen et al. 2007; Eby et al. 2015; Archibald et al. 2017; Nieman et al. 2021a), and our understanding of these regimes and their effects in the rest of Africa remains patchy. This is particularly true for moist miombo woodlands, which are a type of savanna found on nutrient-poor soils in areas where the mean annual rainfall exceeds 1000 mm (Frost 1996). Concerns have been expressed that frequent burning may be detrimental to ecosystem stability and conservation in the catchment of the Okavango Delta. It was therefore decided to quantify the current fire regimes in these catchments, to provide a baseline for monitoring trends, and to identify potential areas of concern.

An early understanding of the effects of fire in miombo woodlands in Africa came about from a few long-term fire experiments, established in the colonial era. The experiments tended to focus on the impacts of fire on the woody vegetation. This was in part because the colonial governments placed a high value on tree cover, in turn in response to the view held by influential colonial botanists that woody vegetation should be the dominant natural cover (Laris and Wardell 2006). Trapnell (1959) reported that high-intensity fires in the late dry season in Zambia were very detrimental for canopy trees in the genera *Brachystegia*, *Jubbernardia*, and *Isobertlinia*, but that burning in the early dry season would allow adequate regeneration, and that complete protection from fire would allow trees to develop fully. Similar findings were reported by Lawton (1978), also from Zambia. Trapnell (1959) noted that miombo tree species could be either fire-tolerant, semi-tolerant (surviving early dry season but not late dry season fires), or fire-sensitive (species that decline under regular burning but that increase when fire is excluded; this group included most of the dominant canopy species). Both Trapnell (1959) and Lawton (1978) proposed a successional pathway that is determined by fire in moist miombo woodland. In the absence of fire, the moist miombo woodland increases in density and becomes dominated by evergreen species to eventually form a tall, dry evergreen forest. On the other hand, repeated exposure to fire converts the miombo woodland to an open woodland of fire-tolerant trees that is dominated by tall grasses. Chidumayo (1988) reported limited findings from a resurvey of the same experimental burning plots described by Trapnell (1959). He found that protection from fire had resulted in a decrease in plant species diversity, largely through the loss of understorey species. He noted that fire protection would increase the risk of destructive accidental fires due to the accumulation of

ground fuels, and suggested that burning early in the dry season would be a more practical management technique for promoting both tree growth and species conservation in miombo without increasing the risk of high-intensity accidental fires. Cauldwell and Zeiger (2000) re-evaluated Trapnell's (1959) classification of the fire-sensitivity of tree species and suggested some changes, but it is clear that current understanding remains imperfect, and that the fire tolerance of individual species needs to be further investigated. Mapaure and Campbell (2002) reported declines in miombo woodland cover in Zimbabwe, related to elephants and fire. They found that elephants (and people) were the major drivers of these declines, but that the role of fire was not clear. It is well known from studies in the Kruger National Park (South Africa) that tree declines are associated with interactions between elephant damage and fires (Shannon et al. 2011; Helm and Witkowski 2012; Vanak et al. 2012), but this is currently unlikely to be a factor in Angola where elephant numbers have been drastically reduced. Ryan and Williams (2011) developed a model to simulate the dynamics of miombo woodlands in relation to fire, based on data from Mozambique and Zimbabwe. The model predicted that large trees were vulnerable to fire, with top-kill rates of up to 12% in intense fires. The modeling showed that miombo tree populations and biomass are very sensitive to fire intensity, and they suggested that this would offer opportunities for effective management by manipulating intensity. Low intensity fires at 2–5-year intervals would maintain the biomass of trees, but both the field experiments and the model predictions showed that annual burning would eliminate most trees.

The available information on fire regimes in Angola is restricted to three studies that used remote sensing. Archibald et al. (2010) used 8 years of burnt area data (from April 2001 to March 2008) from the MODIS satellite to examine fire regimes across southern Africa and summarized information at a country level. In Angola, over 50% of the land area was affected by fire, and much of this area burned more than four times in the 8-year period examined (a mean return period of approximately 2 years). Stellmes et al. (2013) used 11 years of burnt area data (from 2001 to 2012) from the MODIS satellite to examine fire regimes in the Okavango Delta and its adjacent catchment in Angola. Stellmes et al. (2013) recognized four broad vegetation types in their study area (woodlands, including miombo woodlands; savanna; grassland; and wetlands). Overall, fires occurred in the dry season from May to October, and fires in the upper catchment were concentrated in June and July. Stellmes et al.'s study indicated that fires were far less frequent in the miombo woodlands than other vegetation types. For example, the proportion of the area that burnt annually

over the 11-year study period was 3–9% for miombo vegetation types, compared to 12–15% for savanna, 15–25% for wetlands, and 35–40% for grasslands. This was attributed to the relative paucity of grass fuels in miombo compared to the other vegetation types. Using space-for time substitution (see Archibald et al. 2010 for a discussion of the limitations of this method), one would infer that fire return periods for miombo woodlands would be between 11 and 33 years, while those for savanna and wetlands would be 6–8 years and 2.5–3 years, respectively. Catarino et al. (2020) used MODIS data from 2001 to 2019 to examine trends in burning across Angola. They found both increasing and decreasing trends in the frequency of fires, noting that fires were increasing on 10.25% of the 628,000 km² of miombo woodlands in the country, while decreases were restricted to 0.002% of that vegetation type. There have been no ecological studies, other than recent broad species surveys, that have been carried out in the Angolan catchment of the Okavango Delta.

In this paper, we provide an updated analysis of the fire regimes of the Angolan catchment of the Okavango Delta. The analysis differs from that provided by Stellmes et al. (2013) in that it covers a larger proportion of the Angolan catchment (but does not include sections in Namibia and Botswana), over a longer time period (20 vs. 11 years), and uses an updated vegetation map to examine potential fire effects. In addition, we examine the influence of human population density on fire return

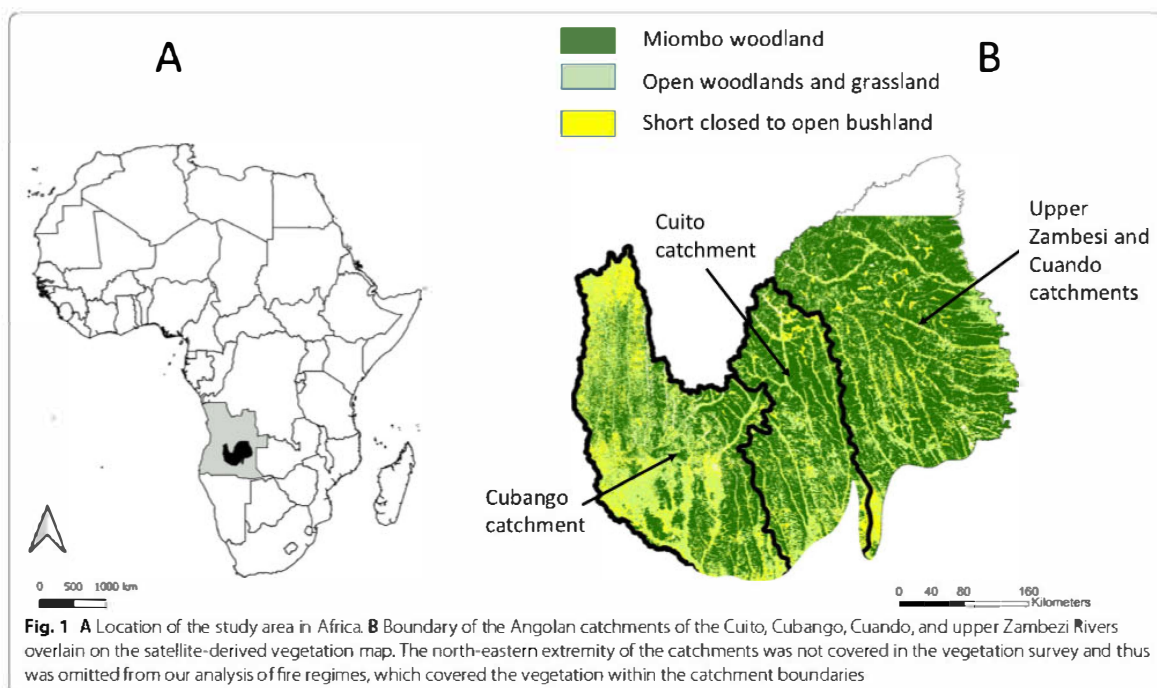
periods and discuss the potential ecological implications of the fire regime for the conservation of the area based on existing understanding of fire effects.

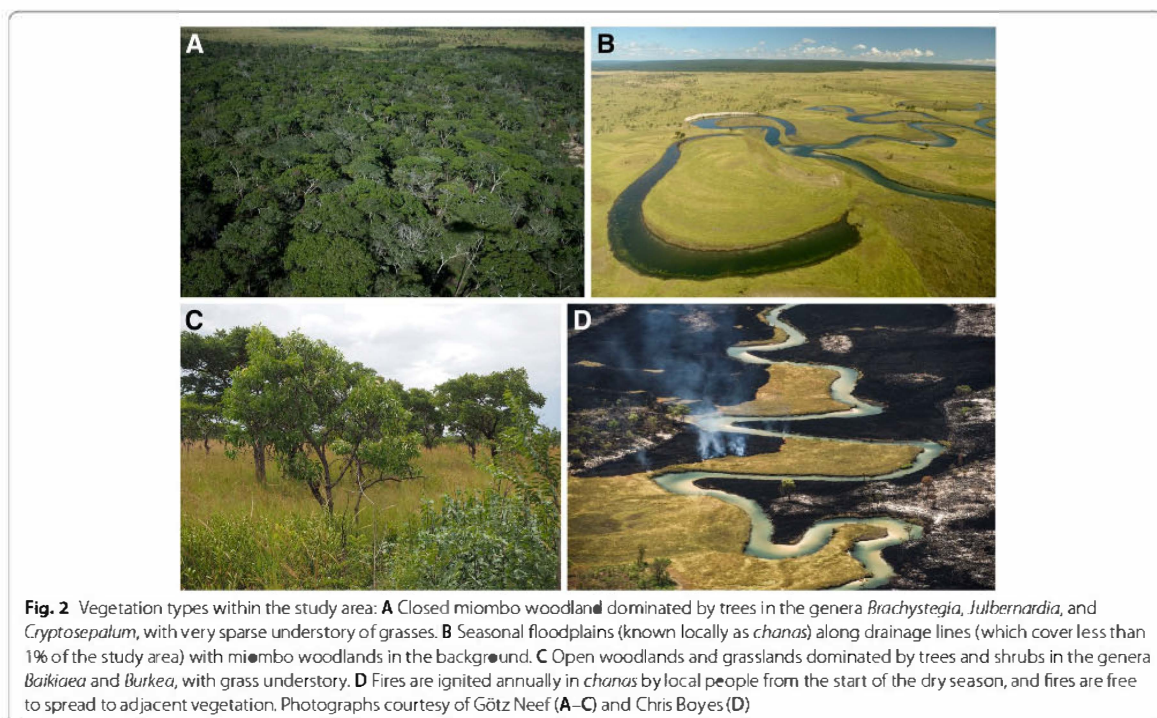
Methods

Study area

The study area (16.4 million ha) included the Angolan catchments of the Cuito and Cubango Rivers, as well as the catchment of the Cuando River, and about half of the catchment of the upper Zambezi River (Fig. 1). These catchments were chosen because they are the source of all water that flows into the Okavango Delta, and their conservation is thus essential for maintaining vital hydrological processes. Mean annual rainfall in the upper catchments of the Cuito, Cuando, and western Zambezi ranges between 1000 and 1200 mm, while the more elevated upper Cubango catchment receives between 1200 and 1400 mm. Mean annual rainfall is lower (500–600 mm) along the southern border with Namibia (Mendelsohn and Martins 2018; Goyder et al. 2018). Rainfall is strongly seasonal, with 85% of rainfall concentrated between November and March; the dry season from May to September receives only 2.8% of mean annual rainfall (<https://en.climate-data.org/africa/angola/cuando-cubango/menongue-5107/>; accessed 4 December 2021).

The vegetation of the study area (Fig. 2) was mapped by Collins et al. (2019) using 20-m resolution imagery from ESA's Sentinel 2 satellite. Collins et al. (2019) based





their vegetation and land cover map on imagery acquired between January 2017 and April 2018. According to this classification, most (93.3%) of the area is under natural vegetation. Cultivated land and settlements cover a further 6.4% of the area, and the remainder (0.3%) was classified as open water or bare ground. For the purposes of examining fire regimes, we grouped the natural vegetation into three broad classes:

- a) Miombo woodlands (covering 54.6% of the study area), which are tall, closed-canopy woodlands dominated by trees in the genera *Brachystegia*, *Julbernardia*, and *Cryptosepalum*. Goyder et al. (2018) referred to this vegetation type as “moist miombo woodlands,” noting that it covered vast swathes of central and eastern Angola. Goyder et al. (2018) listed common trees as *Brachystegia bakeriana* Hutch. & Burt, *B.longifolia* Benth., *Cryptosepalum exfoliatum* (Hutch.) DuRoi, & Brenan, *Julbernardia paniculata* (Benth.) Troupin, which co-occurred with *Pterocarpus angolensis* DC., *Erythrophleum africanum* (Welw. ex Benth.) Harms, *Baphia massaiensis* Taub., *Bobgunnia madagascariensis* (Desv.) J.H.Kirkbr. & Wiersema, *Guibourtia coleosperma* (Benth.) J. Léonard, *Monotes dasyanthus* Gilg, *M. glaber* Sprague, and *Englerophytum magalimontanum* (Sond.) T.D.Penn.

Grasses are sparse to absent in closed-canopy miombo woodlands, making them far less likely to support spreading fires. In the Cubango catchment the original miombo vegetation has been subjected to large-scale felling of trees, while in the Cuito catchment the vegetation is largely intact, and relatively homogeneous (Mendelsohn 2019);

- b) Open woodlands and grasslands (covering 27.3% of the study area), made up of open-canopy woodlands dominated by trees and shrubs in the genera *Baikiaea* and *Burkea*. We also included smaller areas which had been classified by Collins et al. (2019) as medium to open woodland dominated by *Brachystegia* species, or as open to sparse woodland, typically associated with Kalahari sands. These are referred to as “seasonally burnt savannas” by Goyder et al. (2018), who state that “this habitat is fire-adapted, and is dominated by grasses or by geoxylic suffrutices, plants with large underground woody biomass and seasonal above-ground shoots.”
- c) Short closed to open bushlands (covering 10.2% of the study area) dominated by grasses and short trees and shrubs such as African acacias (in the genera *Senegalia* and *Vachellia*), *Zizyphus mucronata* Willd., *Piliostigma thonningii* (Schumacher) Milne-Redh., and *Combretum* species.

Burnt area data

Data on the timing and extent of fires over 20 years (2000–2020) were obtained from the MODIS burnt area product MCD64A collection 6 (Roy et al. 1999; Giglio et al. 2009, 2016, 2018). This monthly product identifies burn scars at a resolution of 500 by 500 m and provides an approximate (accurate to ± 4 days) date of burning (Giglio et al. 2016). The MODIS data were accessed via the University of Maryland ftp site (fuoco.geog.umd.edu) and the monthly data were processed in R software using the rgdal package to produce the burned area and fire return time data that were further analyzed as described below. This collection of the burnt area product was found to improve the detection of smaller burns and to decrease the temporal uncertainty of the burn date (Giglio et al. 2018). The use of MODIS also allows for direct comparisons between our findings and those of the earlier study by Stellmes et al. (2013). Most (>80%) of African savanna pixels are classified as burnt by MODIS if the proportion of the pixel that burnt exceeds 75%; this declines to 60% if only between 50 and 75% of the pixel burnt (Tsela et al. 2014). Burnt area data were available for the entire catchment, but the vegetation map did not cover 678,000 ha (4%) of the catchment (Fig. 1), so our analysis was based on the area covered by the vegetation map. Vegetation was mapped at a finer scale than the fire data, so fire pixels were allocated to the vegetation type that was dominant within a fire pixel.

Fire return intervals

Intervals between fires have been shown to conform to a Weibull distribution (Moritz et al. 2009). The Weibull shape and scale interval parameters and their confidence intervals were estimated for each of the three vegetation types, and the median fire interval (MEI) was then estimated as $MEI = b (\ln 2)^{1/c}$ where b is the scale parameter and c is the shape parameter (Moritz et al. 2009). The fire return interval prior to the first fire in the record and after the last fire in the record cannot be known, and

so fire return values are censored (Polakow and Dunne 1999). For example, a pixel that burned in October 2004 and June 2010 had three intervals: an open-tailed interval of 2.8 years, a closed interval of 5.3 years, and an open-tailed interval of 10.5 years. Because around 14% of the pixels in miombo woodland experienced no fires during the 20 years examined here (Table 1), we ran analyses only on the pixels that experienced at least one fire. The scale and shape parameters were estimated for each vegetation type, and each population density class (see below) using the Survival package in R, which can accommodate open-tailed intervals.

Influence of human population density

Human population density estimates were available from Mendelsohn and Martins (2018), who surveyed households and villages at a scale of 1 ha. To examine the effects of human population density on fire return intervals, we calculated the number of human settlements in each MODIS pixel. This continuous variable was categorized into human population density classes (none = 0, low = 1–10, medium = 11–50, and high > 50 settlements per 10 km² respectively). The combination of three vegetation and four human population density classes resulted in a three by four matrix amounting to 12 different land cover combinations. We randomly selected 200 MODIS pixels from each of these land covers and extracted the burn dates for all fires occurring in any of these pixels. These were used to estimate intervals between fires at each pixel. Median fire return intervals were estimated for each class, as described above. In addition, we used the Weibull shape and scale interval parameters to illustrate the cumulative forms of fire frequency distributions [where $f(t)$ is the probability of a successive fire at time t] for each vegetation type and human population density class separately, using the formula below (Moritz et al. 2009).

$$f(t) = ct^{c-1}/b^c \exp(-(t/b)^c)$$

Table 1 Extent of area burnt, and features of the fire regime. Data are for three major vegetation types that collectively cover 92.1% of the catchments of the Cuito, Cubango, Cuando, and upper Zambezi Rivers

Vegetation type	Total area (km ²)	Total area burnt in successive fires over 20 years (km ²)	Median fire return period (years)	Proportion of area that remained unburnt (%)	Dominant fire season
Open woodlands and grasslands	30,359	204,209	1.85	0.57	June–September
Short closed to open bushland	14,195	100,024	2.23	0.69	June–September
Miombo woodlands	93,457	179,611	4.50	13.9	August and September

Fire seasonality

We examined the seasonality of fires by determining the area burnt every year in each month for each vegetation type. Comparisons were made using a Kruskal-Wallis H test (as data were not normally distributed), followed by a post hoc Wilcoxon rank sum test. P -values were not adjusted and were considered significant when $P < 0.05$.

Results

Fire return intervals

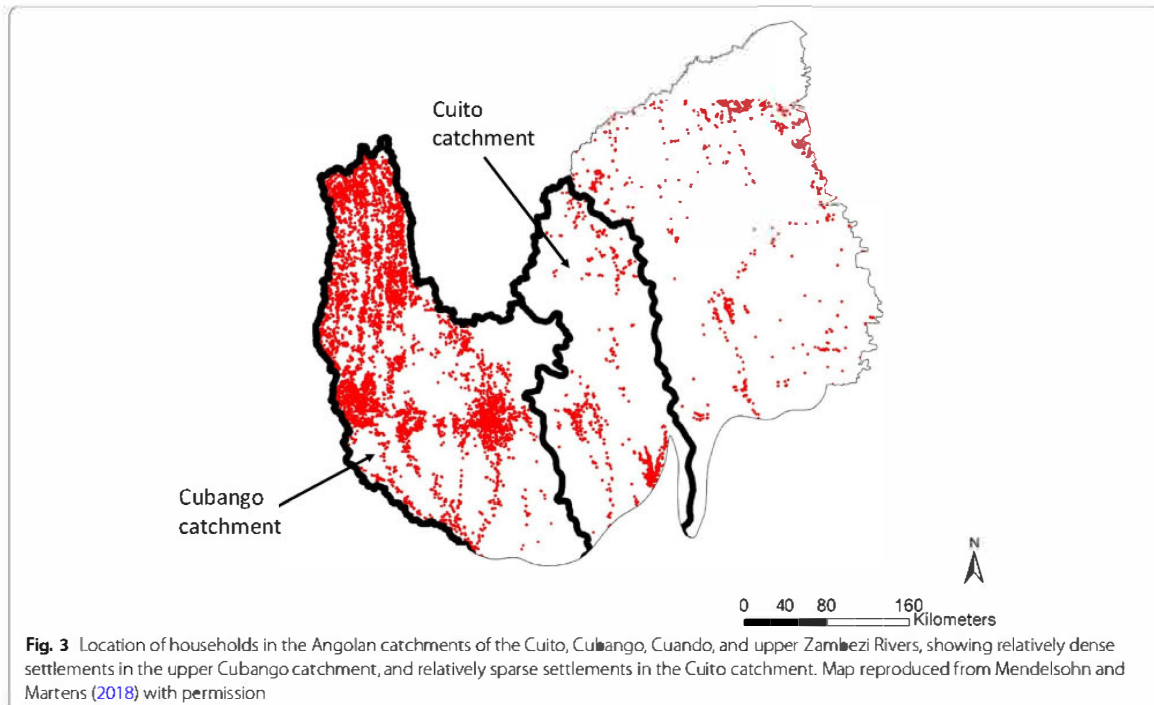
The median fire return intervals differed between the vegetation types. The median fire return intervals for both the short bushlands, and open woodlands and grasslands were relatively short (2.2 and 1.9 years respectively, Table 1). The miombo, on the other hand, showed two distinct fire regimes—most pixels burned fairly frequently (median return interval of 4.5 years) but ~14% of the area was not observed to burn during the period examined here. Most fires in all vegetation types occurred soon (i.e., within 2 years after a previous fire in short bushlands and open woodlands, and within less than 5 years in miombo woodlands), but a small proportion of the area experienced longer intervals between fires (up to 10–15 years).

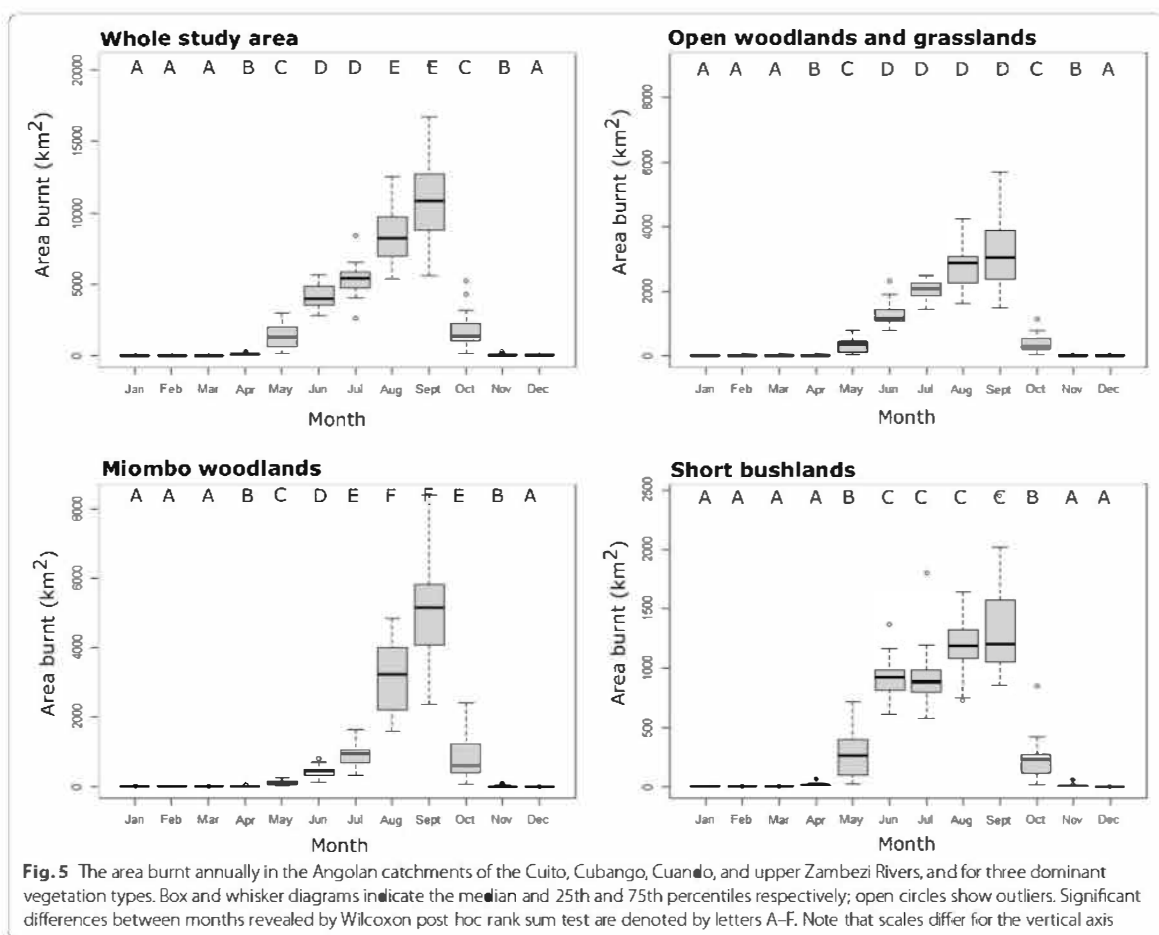
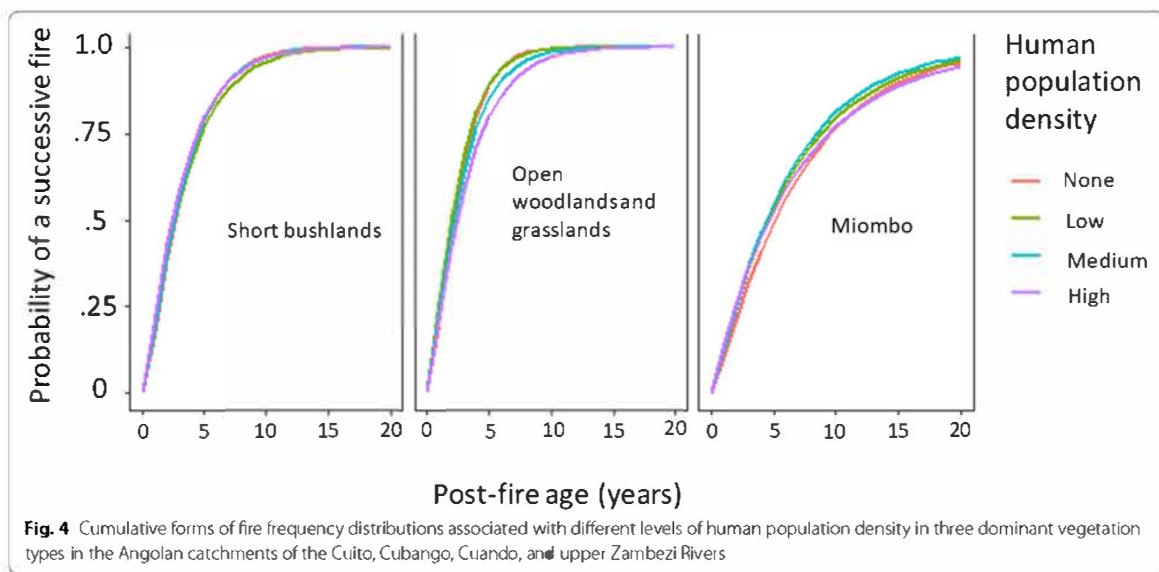
Influence of human population density

Mendelsohn and Martins (2018) estimated that the population was 17 times higher in the Cubango than in the Cuito catchment (estimated populations of 1,466,942 and 85,954 respectively, Fig. 3). Human population density nonetheless had no discernible effect on the fire return intervals in either short bushland or open woodland and grassland vegetation (Fig. 4), and this remained at around 2 years in all classes of human population density (see Supplementary Table S1 for parameters associated with Weibull analysis for each of the vegetation type/population density classes). Fire return intervals were twice as long in miombo woodlands, and the proportion of this vegetation type that burnt was influenced by human population density. The proportion that did not burn during the period examined was 11.5 % where settlements occurred, whereas 19.0% of the sites remained unburnt where people were absent.

Fire seasonality

Fires in the study area began early in the dry season in May and increased through June and July, with significantly larger areas burning in the late dry season in August and September (Fig. 5). No fires were detected in either January or December. The seasonal pattern of burning differed between the vegetation types. The





dominant fire season included the 4 months from June to September in the open woodlands, and in short bushlands. Although the area burnt per month increased as the dry season progressed in these two vegetation types, the differences were not significant (Fig. 5). In miombo woodlands, on the other hand, fires were concentrated in the late dry season, with 78.3% of the area burning in August and September alone (Fig. 5).

Discussion

Fire regimes in the study area

The fire regimes reported here are broadly typical of those found in African savanna woodlands (van Wilgen et al. 2000; Nieman et al. 2021a), where fires are relatively frequent, but with skewed distributions around the median due to a few smaller areas remaining unburnt for longer periods. In the populated parts of our study region (i.e., the Cubango catchment, Fig. 3), people commence burning along drainage lines (known locally as *chanas*, and which cover < 1% of the total area, Fig. 2B) from as early as May onwards in order to promote access and to stimulate new growth for livestock (Kai Collins, personal communication). These fires then spread into adjacent vegetation, and the extent of these fires increases as the dry season progresses (Fig. 5). The density of human settlements had no effect on the frequency of fires, but miombo woodlands burnt less frequently than other vegetation types. The fact that almost twice as much of the miombo remained fire-free where people were absent suggests that people do not change the fire return interval, but that they can alter the amount of landscape that is flammable. People practice slash-and-burn agriculture to grow crops, and these activities are concentrated in the Cubango catchment where most people live. Therefore, miombo woodlands in the Cubango catchment are more likely to be affected by these practices, allowing fire to penetrate what was previously a fire-resistant vegetation type. Chidumayo and Kwibisa (2003) found that woodland clearing increased grass biomass by 20–50% in miombo woodlands in Zambia, which would allow them to burn more readily.

Miombo fires may be concentrated later in the fire season (Fig. 5) because they require a longer period of drying before they can support spreading fires, presumably due to a higher cover of trees and lower grass fuel loads. The likelihood and intensity of fire in undisturbed miombo woodlands would presumably also increase in years of below-average rainfall due to lower prevailing relative humidity. There are reports of extensive clearing of miombo woodlands around settlements in Angola in recent times, including in and around the Cubango catchment (Mendelsohn 2019; Schneibel et al. 2013). Unexploited miombo woodlands are dominated by

fire-sensitive trees (Trapnell 1959; Lawton 1978), suggesting that closed-canopy miombo woodlands developed under a regime of very rare fires, or fires of lower intensity. Where people are present, clearing of these areas has presumably led to the introduction of fires into previously undisturbed, closed-canopy miombo stands, as indicated by the data reported here. Further studies on the ground will be required to improve understanding of the factors that contribute to changing fire regimes. It is also true that the remotely sensed data product used is known to be poor at identifying fires under tree canopies (Tsela et al. 2014) but the closed canopy miombo in this region is not known to burn (M. Finckh, personal communication).

Ecological effects of fire

In the open woodlands, grasslands, bushlands, and *chanas* of our study area, fires occur frequently, and such vegetation types are resilient to regular fire (e.g., Bond 1997; Trollope 1984; van Wilgen 2009), especially in areas of higher rainfall (> 650 mm, Sankaran et al. 2005). There is no evidence that the current regime of regular dry-season burns would be ecologically harmful, except in the case of miombo woodlands. Miombo woodlands in our study area were characterized by fires every 4–5 years or so in the late dry season, but there are some sites that did not burn at all, more so where people were absent. There has been no research into the fire ecology of the miombo woodlands of our study area. Studies reported from miombo woodlands elsewhere in southern and central Africa (reviewed in the Background section above) clearly indicate that high intensity, late dry season fires are harmful to trees, while early dry season fires allow for their survival and persistence. Felling trees in previously fire-free areas will open these areas up and allow fires to burn, and this will be detrimental to the remaining trees because these fires are concentrated in the late dry season. Should this continue, remaining areas of closed-canopy miombo may be converted to open grassy areas characterized by more frequent fires.

Implications for management

Approaches to achieve conservation goals in the Cubango and Cuito catchments are currently being developed following decades of neglect. In 2020, the Wild Bird Trust initiated the Lisima Watershed Partnership in collaboration with local communities, the Angolan government, and relevant NGOs. The primary goals of the partnership are to minimize ecological threats in the area and to improve the livelihoods of local communities. Thus far, the partnership has initiated several ecological studies (of which this paper is one), established a community conservation working group, is constructing a base

from which the partnership's activities will be run, and is preparing an integrated land management plan for the region. The findings of this study will be of relevance for the management plan.

Managers of savanna-protected areas in Africa have developed a relatively wide range of approaches to fire management (van Wilgen 2009; Nieman et al. 2021b). The management of fires in extensive, remote, and relatively inaccessible areas will nonetheless always be challenging. As a result, and in cases where there is no strong evidence to suggest that the current fire regimes are detrimental, managers could choose to adopt a *laissez faire* approach, not attempting to do any prescribed burning, or to prevent, suppress, or contain fires (e.g., Ribeiro et al. 2017). In miombo woodlands, however, there is evidence that fires can be detrimental if they are intense. A goal of management should therefore be to protect the remaining closed-canopy miombo stands from further clearing, and to attempt to shift the timing of burns to the early dry season to reduce their intensity. A shift from burning predominantly in the late dry season to the early dry season will also have the added benefit of reducing significant greenhouse gas emissions that have been attributed to burning in the late dry season (Lipsett-Moore et al. 2018). Research has shown that, while managers have difficulty in changing the proportion of the area that will burn every year, they can influence the seasonal distribution and spatial configuration of fires (e.g., van Wilgen et al. 2004; Brockett et al. 2001), provided that there is sufficient management capacity to do this sustainably over long periods.

Implications for the conservation of the Okavango Delta

Although the Okavango Delta was not included in our assessment of fire regimes, it is well understood that the ecological health of wetlands is closely linked with processes in their catchment areas (Blumenfeld et al. 2009). These processes include the hydrological cycle, which in turn is affected by tree cover, and by fire. Trees are important regulators of water flow from catchments to downstream ecosystems (Bosch and Hewlett 1982; Woodward et al. 2014), and changes in these flows can alter the structure and functioning of wetlands (Larsen and Harvey 2010). Excessive burning in catchment areas can also lead to hydrological changes, and to increased erosion and subsequent siltation (Kotze 2013). Clearing of trees in miombo woodlands and the consequent introduction of fire into this fire-sensitive vegetation type are a cause for concern with respect to the ecological stability of the Okavango Delta, and addressing these issues should be a key component of any plans for ongoing conservation efforts in the area.

Conclusion

Our study has confirmed that fire regimes in the savanna vegetation of the study region are typical of those documented in other African savannas. However, we found that miombo woodlands are characterized by two distinct fire regimes. At some sites fires are relatively frequent, while others do not burn at all. The proportion that does not burn is much higher in areas where human settlements are absent, suggesting that human activity can lead to structural changes to the vegetation that will enable previously fire-free areas to burn. These changes can be detrimental to fire-sensitive trees that dominate undisturbed miombo woodlands, especially if the fires take place in the late dry season when intensity will be high. Such changes could potentially be avoided if undisturbed miombo woodlands can be effectively protected, and if low-intensity burning in the early dry season can be encouraged, although the practical achievement of the latter goal on a large scale will be challenging. Changes to the fire regimes in the Angolan catchments of the Okavango Swamps in Botswana are also a cause for concern, as they could affect hydrological processes on which the Okavango is dependent.

Abbreviations

ESA: European Space Agency; MODIS: Moderate resolution Imaging Spectroradiometer; MEI: Median fire return interval; NGOWP: National Geographic Okavango Wilderness Project; UNESCO: United Nations Educational, Scientific and Cultural Organization.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42408-022-00138-3>.

Additional file 1: Table S1. Parameters associated with Weibull distributions fitted to censored fire return intervals.

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Authors' contributions

This study was collaboratively conceived and designed by BWVW and HMdEK. MS sourced and analyzed remotely sensed data. SA conducted Weibull analyses and assisted with interpretation. The paper was written by BWVW with input from other authors, and all authors read and approved the final manuscript.

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Availability of data and materials

Results of the Weibull analysis are available in the [supplementary material](#). The copyright of the digital vegetation map resides with Wild Bird Trust. All Intellectual Property Rights regarding the production and mapping methodologies of the digital land-cover data reside with GeoTerraImage (GTI) Pty Ltd. Wild Bird Trust has the sole right to authorize distribution and use of the digital land-cover/use and terrain data and accompanying report. Data on human population density in the study area is available at [the-eis.com/etlibrary/sites/default/files/downloads/literature/SE%20Angola%20Population%20mapping.zip](https://www.eis.com/etlibrary/sites/default/files/downloads/literature/SE%20Angola%20Population%20mapping.zip). Data on the timing and extent of fires was obtained from the MODIS burnt area product MCD64A collection 6. MODIS data can be downloaded free of charge at <https://lpdaac.usgs.gov/products/mcd64a1v006/>.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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