



Fire regime of peatlands in the Angolan Highlands

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Abstract The Angolan Highlands region includes the Angolan miombo woodland ecoregion which supports miombo woodland, grasslands, subsistence agricultural land, and peatland deposits. Extensive fires, slash and burn agriculture, peat fuel extraction, and peatland drainage are among the anthropogenic practices that threaten these peatland deposits. Peat fires cause peatland degradation, release significant

amounts of greenhouse gases, deteriorate air quality, and contribute towards climate change and biodiversity loss. This study presents an analysis of the fire regimes over the period 2001 to 2020 in an understudied area of the Angolan Highlands. Moderate Resolution Imaging Spectroradiometer (MODIS) fire and vegetation data were used in combination with a land use/land cover (LULC) classification map to calculate fire frequency, burn area, and fire regimes. The fire patterns within the study site are comparable to those found in African woodland savannas. Across the study site, 6976 km² (11.31%) of the land surface area burned at least nine times from 2001 to 2020, occurring largely within in the river valley environment. Considering the different LULC classes, peatlands were calculated to (a) burn more frequently (average fire frequency from 2001 to 2020=9.12), (b) have the smallest proportion (4.11%) of area which remained unburnt over the fire archive, and (c) have the largest average proportion (45.65% or 746 km²) of burnt area per year. Peatland burning occurred predominantly during drier months from May to September. The results of this study highlight the strong influence of LULC on the fire frequency and distribution in the study area, requiring unique fire management strategies. As has been documented for boreal and tropical peatlands across the globe, we stress the importance of peatland conservation and protection; continued unsustainable management practices may lead to the loss of these important peatland deposits.

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Introduction

The Angolan Highlands are hydrologically and ecologically important, supporting miombo woodlands (Mendelsohn, 2019), grasslands, subsistence agricultural land, and peatland deposits (Lourenco et al., 2022a). Peatlands are terrestrial ecosystems that facilitate the growth of peat, an organic-rich soil that consists of partially decomposed organic matter derived from plant material (Dargie et al., 2017; IPS, 2021; Lourenco et al., 2022b). Peatlands provide multiple ecosystem services that are significant to the United Nation's Sustainable Development Goals, including water filtration, carbon storage, supporting biodiversity, and aid agricultural production and food security (Food and Agriculture Organisation: FAO, 2020). Apart from the natural store of fossil fuels, peatlands are the largest natural terrestrial carbon store and are important in regulating global climate (Friedlingstein et al., 2019; Rieley & Page, 2016; Xu et al., 2018). Due to the Angolan Civil war from 1975 to 2002 and widespread minefields, the eastern Angolan Highlands region remains under-studied (Conradie et al., 2016; Midgley & Engelbrecht, 2019). However, a recent land use/land cover (LULC) classification for the region estimates that the extent of peatlands is at least 1634 km² within an area spanning 61,590 km² (Lourenco et al., 2022a).

Across Africa, fire is considered to play an integral role in the structure and distribution of ecosystems and biodiversity, and influences biochemical cycles (Wei et al., 2020). Fire determines the distribution, ecology, and maintenance of African savannas and grasslands (Catarino et al., 2020) and is the second most important driver of vegetation patterns in savannas after precipitation (Wei et al., 2020). Regular burning maintains savanna vegetation that could otherwise transition into closed woodlands (Bond et al., 2005). Uncontrolled fires, however, can damage agricultural lands and woodlands that are not fire resistant, contributing to deforestation, biodiversity loss, harmful gas emissions, and climate change (Catarino et al., 2020). Africa accounts

for approximately 70% of the global burned area and 50% of fire-related carbon emissions (Andela & Van der Werf, 2014; Van der Werf et al., 2010), but despite this, little has been reported regarding peatland burning across the continent.

Emissions from peat fires are estimated to be 122 Mt C/year (Miettinen et al., 2017), equivalent to 15% of global annual anthropogenic emissions (Che Azmi et al., 2021). Peat fires have been identified to not only release substantial amounts of carbon dioxide and other greenhouse gases (GHGs) but also cause significant damage to peatland deposits and their ecology, contributing to climate change, biodiversity loss, and changes to LULC and ecosystems over time (Page & Hooijer, 2016; Vetrina & Cochrane, 2019). Peat fires may cause prolonged and extreme periods of smoke pollution (haze) that is damaging to human health (Marlier et al., 2013; Page et al., 2002). The role of fire and related peat degradation is well documented in the tropical peat deposits of South-East Asia and South and Central America (Page & Hooijer, 2016; Page et al., 2002, 2007, 2011; Rieley & Page, 2016). The Angolan Highlands landscape and peat deposits are threatened by anthropogenic practices such as extensive fires, slash and burn agriculture, wood and peat fuel extraction, tree clearing, and wetland drainage and overgrazing (Conradie et al., 2016; Taylor et al., 2018).

In Angola, fires are predominantly grass-fuelled (Catarino et al., 2020). Grass vegetation grows in areas such as savanna, grassland, and transition zones (Archibald et al., 2010; Catarino et al., 2020; Huntley et al., 2019). Across sixteen African countries in the southern hemisphere, Angola was identified to have the largest proportion (>50%) of burned area from 2001 to 2008 (Archibald et al., 2010). A recent study for the region provides an analysis of the role of human settlement on miombo woodland fire regimes in the interest of management and conservation (Van Wilgen et al., 2022). The objective of this study is to analyse the spatiotemporal dynamics of fire, the relationship between fire and LULC classes in the Angolan Highlands, focusing specifically on peatland fire regime, and to provide an assessment of peatland response to burning. Understanding fire regimes and their inter-annual variability is critical, not only to identify fire related patterns in the ecosystem but also aids in peat fire management strategies and the assessment of associated human impacts.

Methods

Study area

The Angolan Highlands are part of an extensive interior plateau, characterised by a vast peneplain of Kalahari sand (Goyder et al., 2018; Huntley et al., 2019), and is the primary water source region for the Okavango Delta, a UNESCO World Heritage Site (Marazzi et al., 2017). The climate is strongly seasonal, with hot, wet conditions during the summer months from October to May, and cool, dry conditions during the winter months from June to September (Abiodun et al., 2019; Huntley et al., 2019). Rural communities in the region are dependent on subsistence agriculture which contributes to their food security (Afonso et al., 2020; Hunter & Crespo, 2019). The study site is in the south-east of Angola, predominantly within Moxico province, spanning a latitudinal range of 11°54′–13°54′S and longitudinal range of 18°05′–20°34′E, and covering approximately 61,590 km². The LULC classification

map produced by Lourenco et al., (2022a, b) includes six land cover classes: peatland, miombo woodland, valley grassland, upland grassland, water, and cleared/cultivated land (Fig. 1).

The LULC of the study area (Fig. 1) was classified using 20 m resolution imagery from the Copernicus Sentinel-2 satellite and 30 m resolution imagery from the USGS Landsat 8 satellite (Lourenco et al., 2022a). The map is based on imagery acquired from each satellite from March 2017 to February 2021 (Lourenco et al., 2022a). Ground-based data obtained by the National Geographic Okavango Wilderness Project (NGOWP) was used as training data for this classification over the same period (Lourenco et al., 2022a), and later validation following a field campaign in June 2022. This is a conservative estimate of the LULC as the estimates are derived from the agreement between the two separate LULC classifications (Lourenco et al., 2022a). The use of a single classification results in a higher extent estimate for each LULC class. No other LULC maps that classify

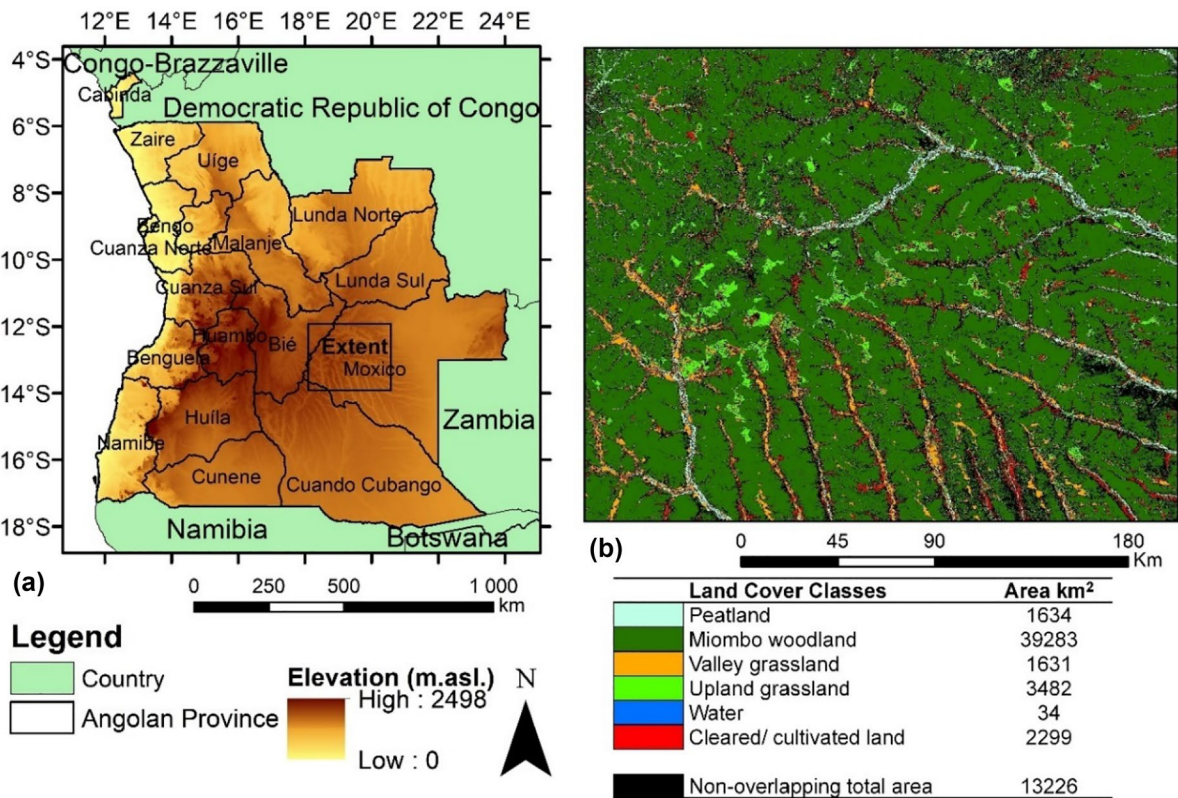


Fig. 1 a Study area map showing the study site extent in Angola and b the LULC of the study area

peatland as a distinct LULC class have been generated before this period for the region.

Peatland accounts for 3.38% of the mapped region (Lourenco et al., 2022a), occurring within the river valleys which are characterised by extensive wet grasslands and ox-box lakes (Conradie et al., 2016). A total of 94 plant species are associated with peat soils (Goyder et al., 2018), reflecting a large variation in vegetation cover. The peatlands are minerotrophic and have formed in lake environments, river floodplains, and on terraces (Lourenco et al., 2022a). Peatlands are drained for cultivation and peat is also extracted as a fuel source (Taylor et al., 2018). Miombo vegetation accounts for 81.22% of the mapped region and grows mainly on the hills surrounding the river valleys. The miombo woodlands contain over 8500 plant species and are dominated by *Brachystegia* (WWF, 2022). This genus of tree provides habitat to wildlife and supports the livelihoods of local communities who use the wood to produce charcoal and building materials (Huntley et al., 2019). Communities often clear the miombo woodlands for agriculture and ranching, and cleared/cultivated land (4.75%) occurs in small patches within the miombo woodland and adjacent to the main rivers and tributaries (Lourenco et al., 2022a). The upland grasslands (7.20%) occur as distinct features on the landscape and contain sporadic trees and shrubs and are dominated by grassland species (Goyder et al., 2018).

Data acquisition

Due to the large scale and challenges in accessing the region, the study required the use of remotely sensed (RS) data. Google Earth Engine (GEE) has an extensive catalogue of RS datasets that have been used for multiple applications, including land cover classifications (Mutanga & Kumar, 2019), wetland mapping (Mahdianpari et al., 2017, 2019), vegetation (Huang et al., 2020), and fire-related studies (Bar et al., 2020; Parks et al., 2018). This study makes use of the MODIS FireCCI51 fire data (Chuvieco et al., 2018a). This product has been extensively validated for wildfires and larger burns (Hall et al., 2021), is shown to have a higher detection of smaller fires (< 1 km²) compared to other products (Katagis & Gitas, 2022), and has comparable accuracy in detecting tropical peatland fires (Vetruta et al., 2021). Despite this, limitations of the MODIS burned area data have been documented

in the literature (Alves et al., 2018; Chuvieco et al., 2018b; Ying et al., 2019), with omission errors up to 72% (Boschetti et al., 2019).

The MODIS FireCCI51 fire data were extracted for the full available data archive from 01/01/2001 to 31/12/2020 for the study site from GEE. The FireCCI51 fire product contains two product dataset layers: “BurnDate” and “Confidence Level” (Chuvieco et al., 2018a). The day for which the first burn was detected (day of the year 1–366) was extracted for each year in the time series and pixels with > 70% confidence level (probability that the classification of the burn area is correct) were retained. To provide an estimate of the burn area omission for the MODIS FireCCI51 fire product, we compared the burn area during 2016 and 2019 to the small fire database for sub-Saharan Africa from Sentinel-2 high-resolution images for 2016 (Roteta et al., 2019) and 2019 (Chuvieco et al., 2022) over the study region. For this comparison, we extracted pixels which had > 70% confidence level in each of the products.

The MODIS MOD13Q1.006 Terra Vegetation Indices 16-Day Global (Didan, 2015) was used to calculate the Normalised Difference Vegetation Index (NDVI) for the time-period 01/01/2001 to 31/12/2020, corresponding to the fire data archive. NDVI is a widely used index for detecting fire risk potential (Michael et al., 2021), fire recurrence (Santana, 2018) and fire recovery (João et al., 2018; Lacouture et al., 2020). The NDVI time-series are particularly useful for assessing the spatial and temporal dimensions of fire (Michael et al., 2021; Santana, 2018). The MOD13Q1 V6 product provides a vegetation index value per pixel, with a 250 m resolution (Didan, 2015). The metadata for the products include a detailed quality assurance bitmask that measures the reliability of the data. Data that is classified in the bitmask as “good” or “useful” were retained (Didan, 2015), whereas data that was contaminated by clouds were excluded from the analysis. All RS data was acquired and processed directly from GEE (Supplementary Material: Table 1).

Fire data and fire detection across LULC classes

Burn frequency and burn area for the study site were calculated at the fire pixel resolution (250 m) over the full burn archive irrespective of LULC for each pixel. Burn frequency was calculated by adding the burn area data layers for each year using the Raster Calculator

tool in ArcMap 10.4. Burn area per year was calculated by totalling the number of burn pixels for each year over the study site and converting the pixel total to a value in km². Burn frequency and burn area were also calculated for each LULC type (Lourenco et al., 2022a). Burn proportion for each LULC class was calculated by dividing the burn area per year for each LULC class by the total classified area for each LULC class. Fire seasonality was calculated from the pixel burn date data and converted to burned area in each month for each LULC type. For this study, we define the beginning of the fire season as the first month of burn occurrence following an extended period of no burn during a calendar year. All data visualisations and processes were performed in Power Query and Power BI, and map visualisations and calculations were performed using ArcMap 10.4 software.

Peatland site NDVI

Reliance on fire data alone may be inadequate in a study region as remote as the Angolan Highlands, where there is no data reported regarding vegetation response to fire. NDVI provides a historical archive of vegetation growth and can be used to obtain a better understanding of the effects of fire on peatlands, which have high variation in vegetation cover and grow near to extensive grasslands (Goyder et al., 2018). The NDVI is a normalised transformation of the near infrared to red reflectance ratio, designed to standardise vegetation index values between -1 and +1 (Didan et al., 2015). The data were used to generate monthly time series of peatland vegetation growth for five specific peatland sites along the Lungu Bungu River (Fig. 2).

Peatlands have been classified from remote sensing (Lourenco et al., 2022a) and validated through ground truthing (June 2022) on two terraces along the Lungu Bungu River. Terrace one, described as the modern river terrace, contains deposits that are almost ubiquitous, whereas terrace two, at a higher elevation to the modern river terrace, is often patchy as peatlands only exist where there are physical features to pond groundwater (Lourenco et al., 2022a). Peatland sites 1, 3, and 5 are on terrace two and sites 2 and 4 are on terrace one (Fig. 2). Fires at these sites were identified by calculating the interception of the fire pixel data with the site polygon over the full fire archive using the Intersect tool in ArcMap 10.4.

Results

Burn dynamics across the study area

Fire frequency

The fire frequency from 2001 to 2020 for individual pixels was calculated for the full study area at 250 m resolution (Fig. 3). There are six different categories based on the fire frequency. The first is the region of the study area that did not experience any detectable fires, representing 18,536 km² (30.05%). This includes large patches in the north-east and south-west and in areas further away from the river valley environment. Fire frequencies of 1–4 were recorded for 22,384 km² (36.29%). Representing the highest proportion, these areas are evenly distributed throughout the study area but not within the river valley environment. During the 20-year archive, a fire frequency of 5–8 is calculated over 13,792 km² (22.36%) of the total land surface area. For the remaining 6976 km² (11.31%), the land surface area burned at least nine times from 2001 to 2020. These more frequently burned areas are shown as large patches in the central and northern regions and are also within the river valley environment. Burn pixels and burn month for each year from 2001 to 2020 for the study site are presented in Supplementary Material Fig. 1.

Burn area

A total of 220,221 km² of the study area was burnt from 01/01/2001 to 12/31/2020, at an average of 11,011 km² (SD. 2999 km²) per year (Fig. 4). The lowest burn areas were calculated for 2001 (5024 km² or 8.14% of the study area), 2020 (5988 km² or 9.71%), and 2002 (6413 km² or 10.40%), and the largest burn areas were calculated for 2019 (16,889 km² or 27.38%), 2017 (15,652 km² or 25.37%), and 2011 (13,953 km² or 22.62%). During the years characterised by low burn areas, fires were distributed predominantly within the river valley environments. During the years with a large burn area, the fires were shown to burn within the river valley environment and spread further into the hilltop regions surrounding the river valleys (Supplementary Material Fig. 1). The burn area omission error for 2016 and 2019 was calculated at 13.82% and 19.30% respectively (Supplementary Material Figs. 2 and 3).

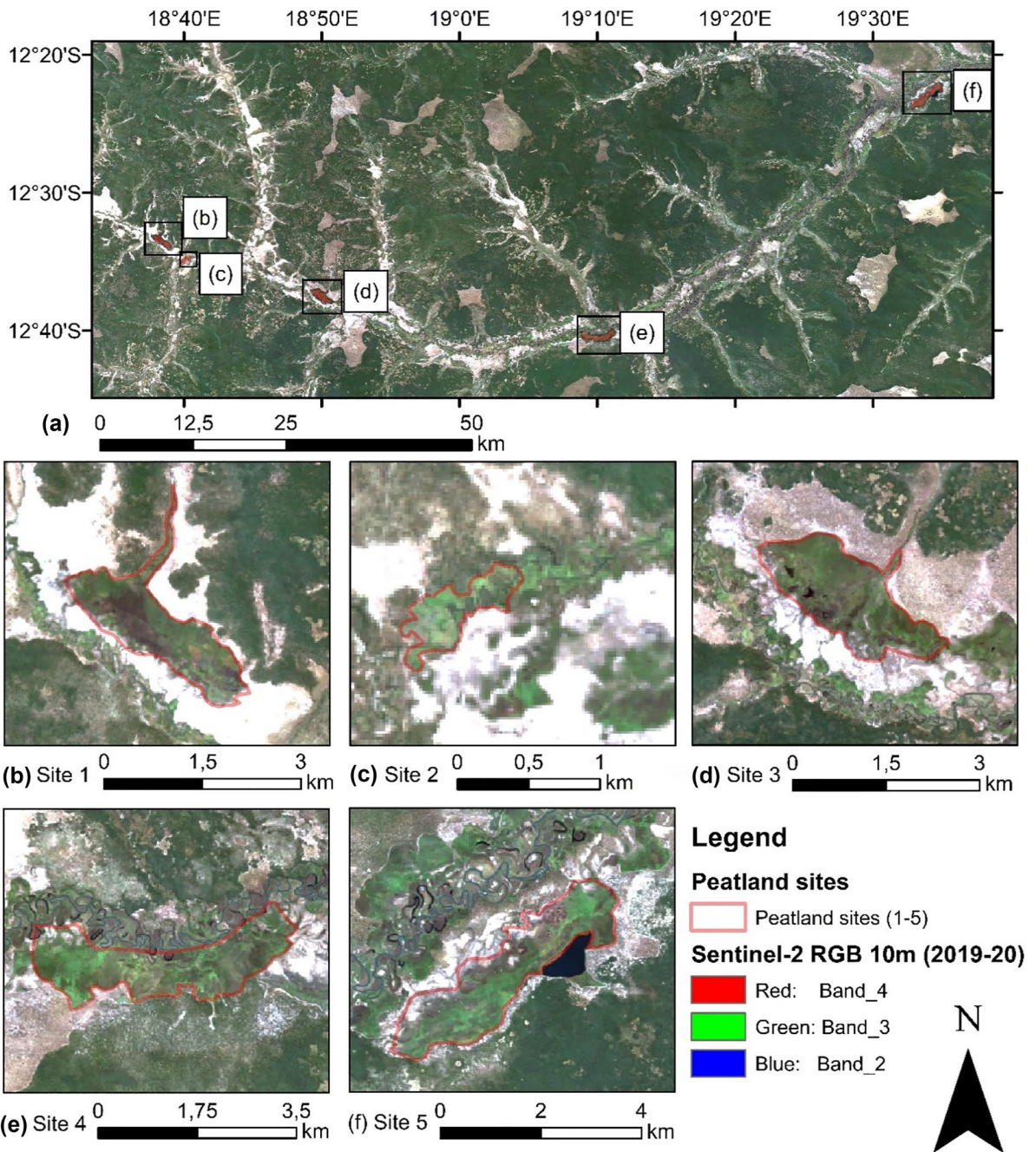


Fig. 2 Peatland sites 1–5 along the Lungu Bungu River

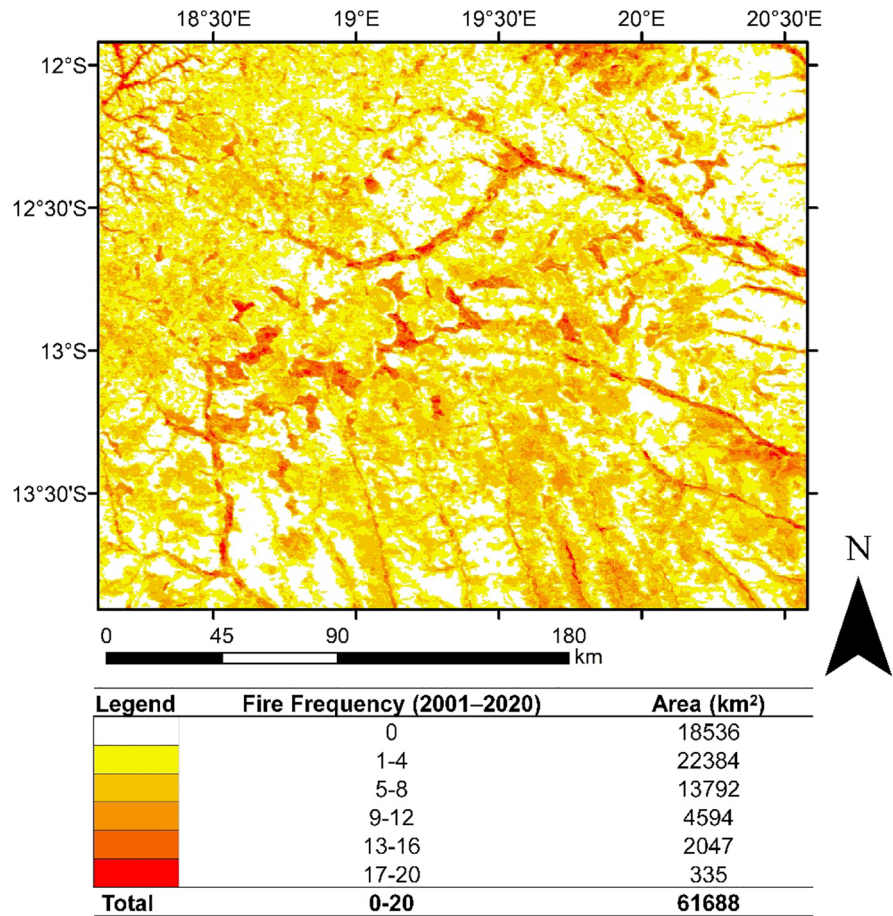
Burn dynamics of LULC classes

Burn proportion and burn area for LULC classes

Burn proportion and burn area for each LULC class were calculated for the 20-year fire archive (Fig. 5).

Peatlands had the largest average burn proportion per year (45.65% of peatland area), followed by upland grassland (40.25%), and the smallest burn proportion was miombo woodland (11.01%; Fig. 5a). In terms of total area burned per year, both miombo woodland and upland grassland burned more than

Fig. 3 Fire frequency per pixel over the period 01/01/2001 to 31/12/2020 at 250 m resolution



peatland, but this is due to these LULC classes having a larger total classified area. On average, 746 km² per year of area classified as peatland is calculated to have burned from 2001 to 2020, with the largest proportion of peatland area having burned during 2019 (58.42% or 955 km²), 2017 (52.58% or 859 km²), and

2005 (50.83% or 831 km²: Fig. 5b). In years of low total burn, peat fires occurred in small patches within the river valley environment. In years of high total burn area, the peat fires expanded to cover larger portions of the river valley environment (Supplementary Material Fig. 1). On average, 4323 km² per year of

Fig. 4 Burn area per year for the study site over the period 01/01/2001 to 31/12/2020

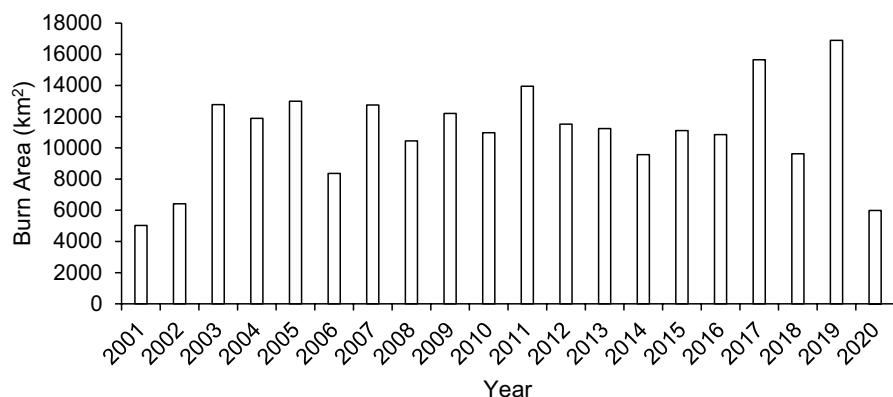
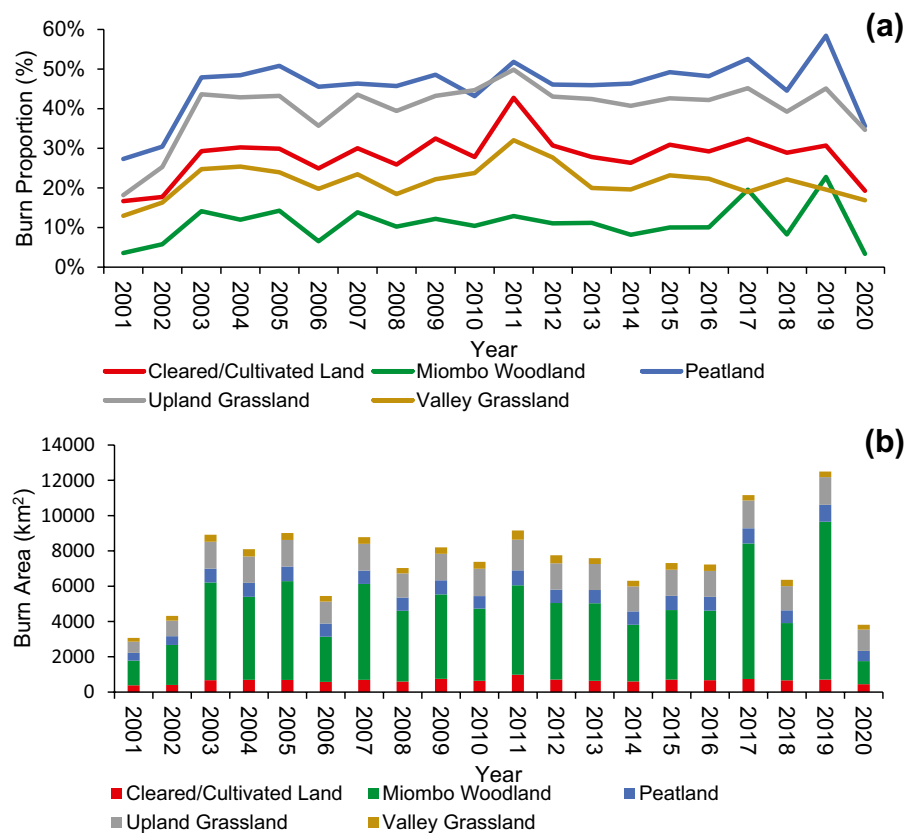


Fig. 5 **a** Burn proportion and **b** burn area per year for each LULC class over the period 01/01/2001 to 31/12/2020



area classified as miombo woodland is calculated to have burned from 2001 to 2020, with the largest proportion of miombo area having burned during 2019 (22.78% or 8949 km²) and 2017 (18.96% or 7680 km²), corresponding to the largest burn area across the study region.

Fire frequency for LULC classes

The average fire frequency for all LULC classes is 3.10 burns from 2001 to 2020 (Table 1). The average fire frequency is the highest (9.12 burns from 2001 to 2020)

Table 1 Average fire frequency for each LULC class

LULC class	Average fire frequency (2001 to 2020)
Cleared/cultivated land	5.64
Miombo woodland	2.20
Peatland	9.12
Upland grassland	8.05
Valley grassland	4.32
All LULC classes	3.10

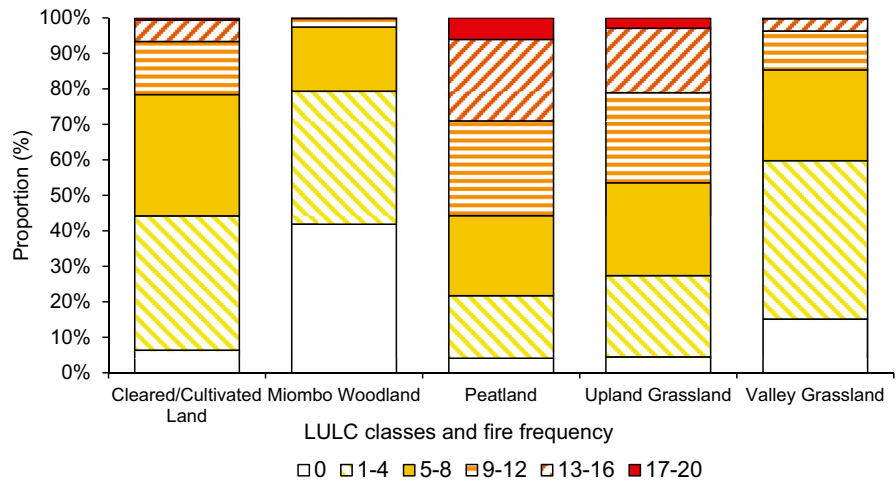
for the peatland class and the lowest for the miombo woodland class (2.20 burns from 2001 to 2020).

The peatland class had the smallest proportion (4.11% or 67 km²) of area that did not burn once and had the largest proportion (6.07% or 99 km²) of area that burned between 17 and 20 times over the 20-year archive (Fig. 6). In addition, the peatland class had the largest proportion of area that burned between 13–16 times and 9–12 times (22.95% or 375 km² and 26.70% or 436 km² respectively). Supplementary material Fig. 4 contains the proportion of area which burned between 0 and 20 times for each LULC class.

Fire seasonality for each LULC class

Over the 20-year fire record, burning starts at the beginning of the dry season during May and continues to the end of the dry season in October for all the LULC classes (Table 2). No fire pixels indicated burning during December. Burn seasonality is generally the same for each LULC class; however, the proportion of burning in each month is different.

Fig. 6 Proportion of area having specific fire frequencies for each LULC class



Over the 20-year record, similar to the other LULC classes, peatland burning started in May and ended in October, where burn proportion was the highest during July (29.37%) and August (26.27%). By contrast, miombo woodland burning started later in June and was concentrated toward the end of the dry season in August (30.26%) and September (57.30%) each year. For valley and upland grassland, the highest proportion of burning occurred during the months of June and July, whereas cleared/cultivated land had the

highest burn proportion in July (23.87%) and August (26.02%).

The average burn area per month from 2001 to 2020 is different for each LULC class (Fig. 7). Average burn area is the highest during July (219 km²) and August (195 km²) for peatland. Miombo woodland had the highest average burn area during August (1,308 km²) and September (2,477 km²). Both valley and upland grassland had the highest average burn area during June and July and cleared/cultivated land has the highest

Table 2 Percentage burn proportion per month for each LULC class over the period 01/01/2001 to 31/12/2020. A colour pallet is used to indicate high or low burn proportion

Month	Cleared/ Cultivated Land	Miombo Woodland	Peatland	Upland Grassland	Valley Grassland	All Classes
January	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
February	0.00%	0.00%	0.01%	0.00%	0.01%	0.00%
March	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
April	0.11%	0.02%	0.09%	0.08%	0.40%	0.06%
May	5.22%	0.51%	4.35%	4.81%	13.25%	2.71%
June	19.64%	2.67%	22.81%	29.04%	33.98%	12.58%
July	23.87%	6.50%	29.37%	30.11%	25.40%	15.61%
August	26.02%	30.26%	26.27%	20.71%	16.04%	27.03%
September	22.36%	57.30%	15.20%	13.79%	9.64%	39.65%
October	2.78%	2.73%	1.88%	1.47%	1.30%	2.35%
November	0.01%	0.01%	0.02%	0.00%	0.00%	0.01%
December	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

average burn area during July (155 km²) and August (169 km²).

Fire seasonality for the peatland sites

Across all five peatland sites, fires only occurred from May to September. Sites 1, 3, and 5 which are on terrace two burned 15, 16, and 18 times respectively over the 20-year fire archive, while sites 2 and 4 which are on terrace one burned 8 and 20 times respectively (Fig. 8). Across the study sites, peatland vegetation growth has a similar seasonal pattern to precipitation in the Angolan Highlands (Supplementary Material Fig. 5). Peatland NDVI is the lowest during August (average of 0.37) each year near the end of the dry season and the highest during December (average of 0.67) during the middle of the wet season. Although not exclusively across all sites, burning generally occurs when average NDVI is the lowest during the calendar year. A comparison between burn years (at least one burn) and non-burn years between all sites reveals a slightly different seasonal pattern (Fig. 8f). During burn years, peatland sites generally have slightly lower NDVI values on average at the start of the growing season (September to November) but have slightly higher values on average at the end of the growing season (January to May).

Discussion

Fire patterns in the Angolan Highlands

The comparable monthly burn area and low omission errors for 2016 and 2019 between the MODIS Fire-CCI51 product and the Sentinel-2 burned area products over the study region support the use of MODIS in calculating fire dynamics in this study. The fire patterns in the study area are broadly similar to those found in African woodland savannas (Meller et al., 2022; Nieman et al., 2021; Van Wilgen et al., 2022). This study found that fire frequency and burn area are higher within the river valley environment. Van Wilgen et al. (2022) suggest that people in the Angolan Highlands region burn vegetation along drainage lines at the start of the dry season to aid accessibility and promote the growth of pastoral vegetation for livestock. The valley environment near rivers is where peatlands, valley grassland, and cultivated land are

located, and the adjacent upland environment supports patches of cultivated land and upland grassland within the miombo woodlands (Lourenco et al., 2022a).

Within Angolan woodland savannas, Meller et al. (2022) determined that the mosaic of woodlands and grasslands is frequently burned by humans. The type of vegetation burned, and the timing and frequency of fire both depend on land management practices (Meller et al., 2022). Grasslands burn in the early dry season (June to July) to aid in hunting practices and clear village surroundings, and woodlands are burnt late in the dry season (August to September) to prepare fields for the growing season (Meller et al., 2022; Teutloff et al., 2021), consistent with the fire regimes for the grasslands and miombo woodlands in the study area. Van Wilgen et al. (2022) hypothesise that humans do not change the fire frequency, but that they can change the amount of landscape that is flammable. Van Wilgen et al. (2022) identified that the density of human settlement had no effect on the frequency of fires, but that a large proportion of miombo woodland remained unburnt in areas where humans were absent. Although we did not directly analyse the influence of human density, the miombo woodlands were calculated to have the highest proportion of area which did not burn.

Peat deposits in the study area were calculated to (a) burn more frequently, (b) have the smallest proportion of area which remained unburnt over the fire archive, and (c) have the largest average proportion of burnt area per year compared to the other LULC types. By contrast, miombo vegetation burnt less frequently and had the largest area which remained unburnt and the smallest average proportion of burnt area per year. Within the peatlands of Sumatra and Kalimantan in Indonesia, Vetruta and Cochrane (2019) calculated that although peatlands covered smaller portions of land area, burning in peatland areas was almost five times larger than in non-peatland areas. Fire frequencies were also higher in non-forested areas than in forested areas in Indonesia (Vetruta & Cochrane, 2019). This highlights the important role of LULC with regard to fire seasonality, burn area, and proportion in the study area.

Patches of dense miombo woodlands in the Angolan Highlands remain unburnt for several years as observed in other regions of southern Africa such as Zambia (Malunga et al., 2022) and Zimbabwe (Mapanda et al., 2012). Burned area increased as

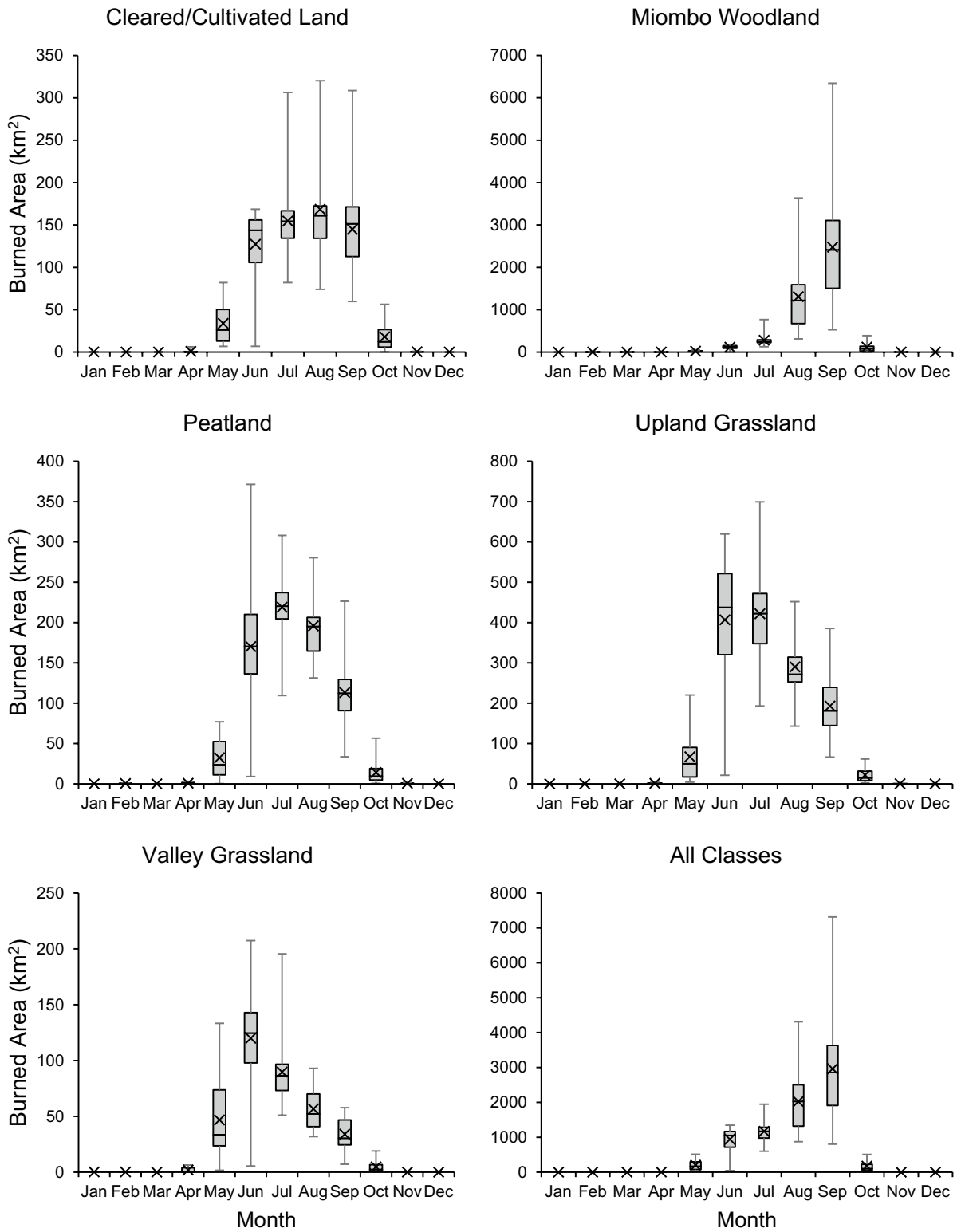


Fig. 7 Box-and-whisker plots of the maximum, minimum, average, mode, and inter-quartile range of the annual burned area for each LULC class and all classes per month from 2001 to 2020

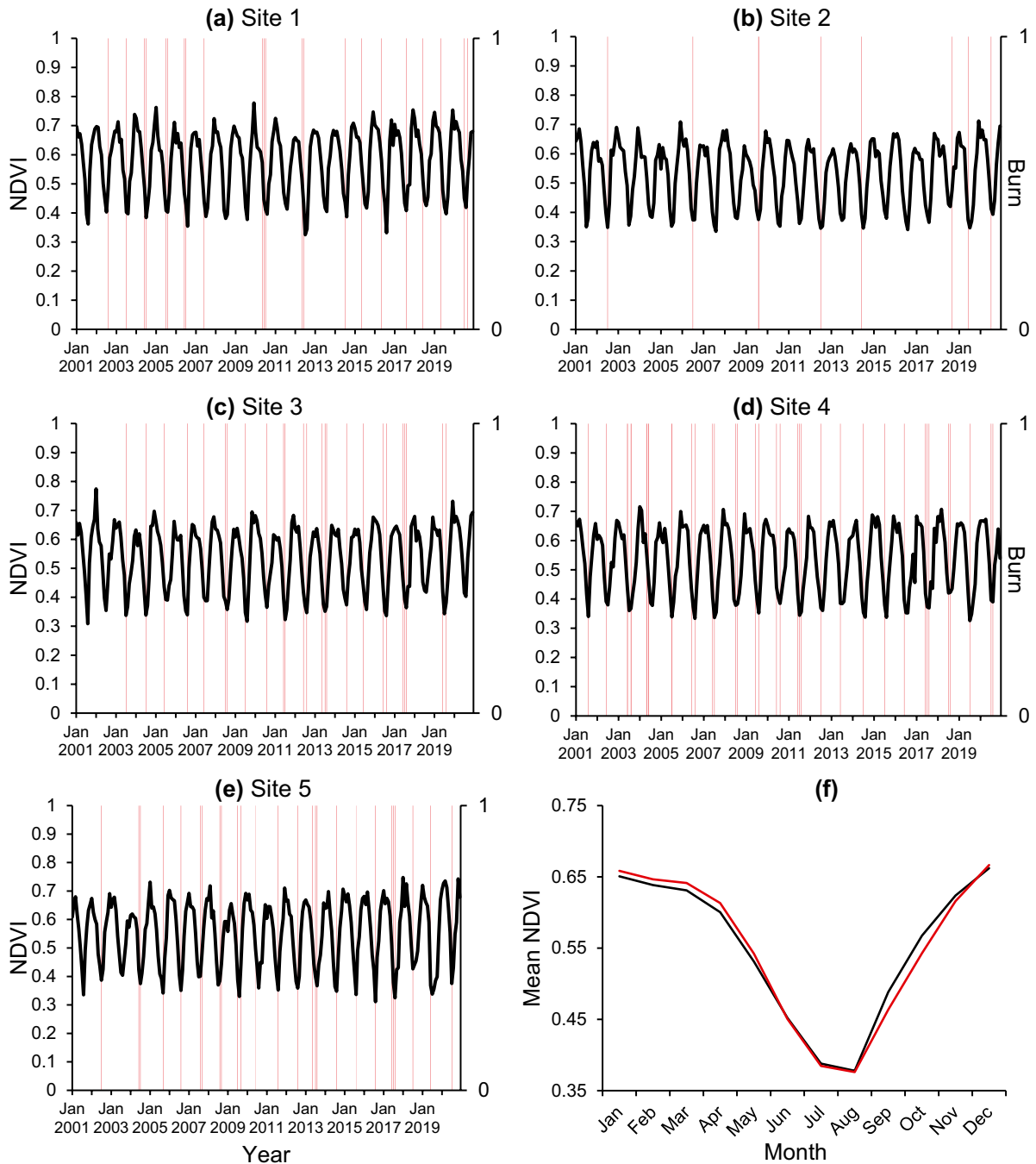


Fig. 8 Peatland vegetation (average NDVI per month) and burn history (2001–2020) for sites 1–5 (a–e). The black line indicates the time series of average NDVI for each month, a burn value of 1 (red vertical line) corresponds to the month in which the peatland burnt. In some instances, fires occurred over mul-

tipale months in the same year, indicating that the peatland site burned in unique locations at slightly different times in the year. **f** Average NDVI per month for all sites during non-burn years (black line) and burn years (red line)

the dry season continued; peatland, cultivated land, upland, and valley grasslands generally started burning at the start of the dry season in May and continued into October towards the end of the dry season. Miombo vegetation was calculated to burn during the late dry season in August and September, consistent with the existing literature concerning Angolan woodland savannas (Meller et al., 2022; Van Wilgen et al., 2022). These late fires, often associated with slash and burn agriculture, are particularly severe due to larger and drier fuel loads (Govender et al., 2006; Meller et al., 2022). The miombo woodlands contain patches of area classified as cleared/cultivated land (Lourenco et al., 2022a), and regular burning of these areas may cause fires to penetrate deeper into the woodland environment (Catarino et al., 2020; Van Wilgen et al., 2022).

Implications of fire for peatlands

Peatland loss and degradation as a result of fire has been documented in boreal and tropical peatlands across the globe (Rieley & Page, 2016; Turetsky et al., 2015; Vetrina & Cochrane, 2019). Peatlands rarely burn due to waterlogging (Rieley & Page, 2016), but desiccated peat is inherently combustible (Vetrina & Cochrane, 2019). Since peatlands have been increasingly drained, they can more easily ignite and become progressively more degraded due to burning as negative feedback (Turetsky et al., 2015; Vetrina & Cochrane, 2019). Across the five ground-truthed peatland sites along the Lungu Bungu River, peatland burning consistently occurred during the month that had the lowest NDVI. The results suggest that peatland burning in the early dry season (May and June) is likely because of burning near peatland margins in close proximity to grassland areas, whereas peatland burning late in the dry season (July to September) is likely due to drainage and drier conditions. During burn years, peatland sites generally had slightly lower NDVI values on average at the start of the growing season (September to November) but had slightly higher values on average at the end of the growing season (January to May). This suggests a time lag of vegetation growth following burning.

Peat fires are dominated by smouldering combustion, which is ignited more readily than flaming combustion and can persist in wet conditions (Page & Hooijer, 2016; Turetsky et al., 2015). In undisturbed peatlands, most of the peat carbon stock is protected

from smouldering, and this resistance has led to a build-up of peat carbon storage in boreal and tropical regions over long timescales (Page & Hooijer, 2016). Drying due to climate change and human activity both lower the water table in peatlands and increases the frequency and extent of peat fires (Page & Hooijer, 2016; Rieley & Page, 2016). The combustion of deeper peat affects older soil carbon that has not been part of the active carbon cycle for millennia (Turetsky et al., 2015). Peat fires can cause permanent land cover conversion and net release of carbon in the atmosphere, unlike savannah or grassland fires where carbon released is balanced by a roughly equivalent uptake over the following growing season (Wooster et al., 2021). This underscores the importance of peat fire emissions to the carbon cycle and feedbacks to the climate system with regard to the Angolan Highlands.

Precipitation in the study area is seasonal and nutrient content of the soil is very low, forcing subsistence farmers to abandon their fields and use fire to clear vegetation and enrich the soil from the ash (Gonçalves et al., 2017; Wallenfang et al., 2015). The rate at which vegetation is cleared and converted into cropland is dependent on the growing human population (Catarino et al., 2020). The close relationship between burning, very dry seasons, and consecutive years of drought promotes an increase in the intensity and occurrence of fire (Hamilton et al., 2022). Drought conditions lead to food insecurity, stimulating communities to drain peatlands for cultivation (Taylor et al., 2018), threatening peatland ecology and functioning (Che Azmi et al., 2021; Page & Hooijer, 2016).

Fire management, future research, and area conservation

Peatlands have considerable economic, ecological, and cultural value (FAO, 2020). Within the study area, peatlands have burn frequencies and fire regimes that are distinct to the miombo woodlands, grasslands, and cultivated regions, requiring unique land management and fire protection strategies. There are two important trends with regard to total burn area that highlight the potential influence of rural communities with regard to fire in the study area. First, total burn area for the study area increased by 99.14% between 2002 and 2003, and this is consistent with what was recorded across unprotected rural areas in Angola (Catarino et al., 2020). Across Angola, the largest burnt areas from 2001 to

2019 were recorded between 2003 and 2005, which was linked to the end of the civil war in 2002 (Catarino et al., 2020). During the war, rural–urban migration was prevalent and agricultural fields were abandoned, and after the war ended, communities returned and started clearing and burning the land for agriculture and grazing (Catarino et al., 2020). By contrast, protected areas across Angola experienced decreasing fire trends during that same period (Catarino et al., 2020).

Second, between 2019 and 2020, total burn area reduced by 64.55%. The World Health Organisation (WHO) officially declared the SARS-CoV-2 a global pandemic on March 11, 2020 (Hiscott et al., 2020), prior to the common burn months in the Angolan Highlands (May to October). Governments were urged by the WHO to adopt strict social distancing and quarantine measures (Hiscott et al., 2020). This in combination with excess burning during 2019 was likely responsible for reduced burning during 2020. Although there is evidence to suggest that there is a strong relationship between area conservation, people, and fire, it is difficult to prove the causal relationship between each of these factors without extensive fieldwork. Remote sensing can reveal temporal and spatial patterns but cannot reveal, unambiguously, the cause of fire (Wooster et al., 2021). Several factors could influence changes to burn frequency, burn area, and seasonality including changes to climate, groundwater level, and natural burn cycles in the vegetation and lightning (Trauernicht, 2019; Wooster et al., 2021). Future research could identify whether spatial patterns of fire can be used to predict the location and timing of fire, and whether the spatial patterns are directly related to land management practices.

The Angolan Highlands study area is unprotected. Currently, there are two protected areas south of the study area, Luengue-Luiana and Mavinga, which are both within the Cuando-Cubango Province (Huntley et al., 2019). The only protected area within Moxico Province is Cameia, located northeast of the Angolan Highlands study site (Huntley et al., 2019). The NGOWP was formed following growing concerns of the threat of environmental degradation in the Angolan catchment of the Okavango Delta. The mission of the NGOWP is to preserve the greater Okavango Basin in its current near-pristine state by establishing a network of new protected areas (National Geographic Society, 2022). Catarino et al. (2020) stress that the conservation of

Angolan woodland savannas is urgently needed. Effective conservation requires that fire plays a role in ecosystems without representing a threat to ecosystems or human health (Shlisky et al., 2007). Conservation strategies should include understanding the ecological and socio-economic roles of fire within the region and place focus on peatland fire and preservation.

Conclusion

This study provides a spatio-temporal analysis of fire regimes in an under-studied area of the Angolan Highlands. This is the first study to report the peatland fire regimes in the study area. MODIS fire and vegetation data was used in combination with a recent LULC map of the study area to determine LULC fire regimes over the period 2001–2020. River valley environments that support peatlands, grasslands, and cultivated land were shown to burn more frequently than the adjacent hilltops which primarily support miombo woodland vegetation. Peatlands were demonstrated to burn more frequently and at a larger proportion compared to other LULC classes in the region. The results of this study highlight the strong influence of LULC on the fire frequency and distribution in the study area. The need for unique management strategies bringing attention to the potentially damaging consequences of fire with regard to LULC change, biodiversity loss, carbon emissions, and climate change in the future. This study is an important step in highlighting the need for conservation efforts in the study area which remains unprotected. Continued lack of sustainable management practices may lead to the loss of important peatland deposits, having consequences on local communities and important ecological systems downstream.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

Competing interests The authors declare no competing interests.

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