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Peat Dynamics in the Angolan Highlands



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830429

A thesis submitted in fulfilment of the academic requirements for the degree of Doctor of Philosophy

School of Geography, Archaeology and Environmental Studies

University of the Witwatersrand, Johannesburg

March 2023

DECLARATION

I declare that this thesis is my own, unaided work, except where otherwise acknowledged. It is being submitted for the Degree of Doctor of Philosophy in Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for examination for any degree at this or any other university.



_____

Mauro Lourenco

22 March 2023 at Johannesburg

ABSTRACT

The Angolan Highlands is a war stricken, threatened, and under-studied area. The region is hydrologically and ecologically important and supports extensive tropical peatland deposits. Peatland preservation has been acknowledged to address climate change, is sensitive to drought and fire, and is directly influenced by vegetation and hydrological conditions. However, little research has been conducted in the Angolan Highlands. This study addresses gaps in the literature through four key contributions. The first is a critical review of peat definitions: the implications of disparate definitions are detailed, and a new proposed definition for peatlands in the interest of climate science is provided. The second is the first map of peatland extent in the Angolan Highlands, containing details on the age and growth dynamics. The study presents a conservative estimate of peatland extent that is much larger than previously estimated for Angola and is a crucial first step in facilitating the preservation of this deposit. The third contribution is the first historical assessment of drought and vegetation response in the region. This contains a 40-year drought and 20-year vegetation history, demonstrating that drought occurrence is increasing and there is a strong relationship between precipitation and the peatland vegetation region. The fourth contribution is the first assessment of the contemporary (2001-2020) fire regime of these peatlands, and reveals that among all land cover classes, peatlands burn more frequently and at a higher proportion. Investigation into the peat dynamics of the Angolan Highlands indicate that they have critical importance and are naturally resistant to both droughts and fire. Failure to preserve these deposits will have direct implications on the communities, environment, and surrounding areas.

Keywords: Angolan Highlands, Carbon, Drought, Fire, Peat, Remote Sensing.

LIST OF WORKS

This study is organised in chapters, four of which are stand-alone research papers that have been accepted for publication in peer-reviewed journals. These are combined with an introduction, study region, methodology, general discussion, and conclusion chapter to present a PhD thesis by publication. The four published papers include:

1. Lourenco M, Fitchett JM and Woodborne S (2022) Peat definitions: A critical review. *Progress in Physical Geography: Earth and Environment,* DOI: 10.1177/03091333221118353

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2. Lourenco M, Fitchett JM and Woodborne S (2022) Angolan highlands peatlands: Extent, age and growth dynamics. *Science of The Total Environment*, 810, 152315. DOI: 10.1016/j.scitotenv.2021.152315

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2. Lourenco M, Woodborne S, and Fitchett JM (2022). Drought history and vegetation response in the Angolan Highlands. Society of South African Geographers Biennial Conference, 12-14 September 2022.

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LIST OF ACRONYMS AND SCIENTIFIC TERMS

~ cal. yr BP: interpolated, calibrated AMS dates calculated using the BACON model; years before present

AMS: Accelerator Mass Spectrometry

API: Application Programming Interface

ASTM: American Society for Testing and Materials

CHIRPS: Climate Hazards Group InfraRed Precipitation with Station data

CMI: Crop Moisture Index

CNV: Cuanavale Source Lake

CO_2: Carbon dioxide

COP: Conference of Parties

CS: Cuito Source Lake

CU: Cuando Source Lake

DEM: Digital Elevation Model

DRC: Democratic Republic of the Congo

ENSO: El Niño Southern Oscillation

ESA: European Space Agency

EVI: Enhanced Vegetation Index

FAO: Food and Agriculture Organization

FAO UNESCO: Food and Agriculture Organization United Nations Educational Scientific and Cultural Organization

GEE: Google Earth Engine

GIS: Geographical Information System

GHG: Greenhouse gas

IPCC: The Intergovernmental Panel on Climate Change

IPS: International Peatland society

ITA: International Trade Administration

ITCZ: The Inter-tropical Convergence Zone

IUCN: International Union for Conservation of Nature

L8: Landsat 8

LB: Lungui Bungu River

LULC: Land use land cover

m.asl: meters above sea level

MODIS: Moderate Resolution Imaging Spectroradiometer

NASA: National Aeronautics and Space Administration

NDVI: Normalised Difference Vegetation Index (NDVI)

NDWI: Normalised Difference Water Index

NGOWP: National Geographic Okavango Wilderness Project

NIR: Near Infrared

NOAA: National Oceanic and Atmospheric Administration

PDSI: Palmer Drought Severity Index

RCM: Regional Climate Model

RDI: Reconnaissance Drought Index

RF: Random Forest

RGB: Red, green, blue

RS: Remote Sensing/ Remotely Sensed

RVAA: Regional Vulnerability Assessment and Analysis Programme

S2: Sentinel 2

SASSCAL: Southern African Science Service Centre for Climate Change and Adaptive Land Management

SF: Surface reflectance

SPI: Standardized Precipitation Index

SPEI: Standardized Precipitation Evaporation Index

SVM: Support Vector Machine

SWIR: Shortwave Infrared

SRTM: Shuttle Radar Topography Mission

TTT: Temperate Tropical Trough

UNESCO: United Nations Educational, Scientific and Cultural Organization

UNFCCC: United Nations Framework Convention on Climate Change

USGS: United States Geological survey

WHO: World Health Organization

WMO: World Meteorological Organisation

WWF: World Wildlife Fund

CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 The Angolan Highlands

Angola has unique habitats and species and is one of the least recognised biodiversity hotspots in the world (Myers et al., 2000; Huntley et al., 2019). Angola is source of many major rivers in southern Africa and is referred to as the “water tower” of the region (Huntley, 2019). These river systems originate from the interior Bié Plateau of the Angola Highlands and flow into large river catchments such as the Cuanza, Cassai (Congo), Lungui-Bungu (Zambezi), Cuito and Cubango (Okavango: Huntley, 2019). The lack of ecological and environmental data and reporting for the upper catchments of the Angolan Highlands is due to historic conflicts in the country (Huntley et al., 2019). The Angolan War of Independence (1961-1974), the Angolan Civil War (1975-2002) and resultant extensive minefields have prevented access and any scientific exploration or study in the region for over 50 years (Conradie et al., 2016; Midgley and Engelbrecht, 2019).

The Okavango Delta, a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage site (International Union for Conservation of Nature: IUCN, 2022), is dependent on precipitation occurring in the highlands of central Angola, where water flows into the Okavango River from two tributaries: the Cuito River and Cubango River (McCarthy et al., 2000; Gumbricht et al., 2004). Concern of the threats to the upper catchments of the Angolan Highlands, and the

potential downstream consequences to the Okavango Delta, resulted in the establishment of the National Geographic Okavango Wilderness Project in 2015 (NGOWP; Quammen, 2017). The aim of the NGOWP is to create a network of newly protected areas to conserve the length of the Okavango Catchment (Quammen, 2017). The NGOWP has funded numerous surveys and led a series of expeditions to document the biodiversity and ecology of the Angolan Highlands (Taylor et al., 2018; Goyder et al., 2018; Skelton, 2019; Barber-James and Ferreira, 2019; Van Wilgen et al., 2022). The findings of these expeditions, surveys and studies are intended to provide a scientific foundation to inform the establishment of a system of protected areas within the Angolan Highlands and for the entire Okavango Catchment (Van Wilgen et al., 2022).

1.1.2 Peat

Exploratory surveys conducted by the NGOWP between 2015 and 2018 identified peat deposits in the eastern Angolan Highlands (Conradie et al., 2016; Goyder et al., 2018). Peat is a type of organic-rich soil that consists of partially decomposed organic matter derived from plant material (International Peatland society: IPS, 2021). Peat forms when the ground surface is waterlogged due to the interaction between landform, climate, and vegetation (Lindsay, 2016). The term peatland refers to both the peat soil and the terrestrial wetland ecosystem growing on its surface (Dargie et al., 2017). Peatlands, representing at least one third of the global wetlands (Parish et al., 2008), are important ecosystems for biodiversity conservation, carbon storage, climate regulation, biomass production and human welfare (Erwin, 2009; Minasny et al., 2019). Peatlands provide multiple ecosystem services that support the Sustainable

Development Goals (Food and Agriculture Organization: FAO, 2020) including purifying water (Frolking et al., 2011; Evers et al., 2016), reduction of flooding and soil erosion (Harenda et al., 2018), aiding in agricultural production and food security (Page et al., 2011), and supporting biodiversity (Minayeva et al., 2017; Xu et al., 2018). Peatlands are the largest natural terrestrial carbon store (Rieley and Page, 2016). Climate change, land use land cover (LULC) change, peatland drainage and fire because of human activities reduce peatland resilience to drought and fire and are linked to peatland degradation, which releases the stored carbon into the atmosphere (Harenda et al., 2018; Minasny et al., 2019). Efforts to reduce the anthropogenic impact on climate has placed great importance on preserving natural carbon sinks such as peatlands (Friedlingstein et al., 2019).

Peatlands are estimated to cover 3% of the global land surface (Page et al., 2011; Xu et al., 2018). Although this is a relatively small area, the role of peatlands in the global carbon cycle is significant (Harenda et al., 2018; Loisel et al., 2021). Globally, peat and peatlands have been recognised as essential to multiple international conventions that protect habitats, biodiversity, carbon sinks and reduce greenhouse gas (GHG) emissions (FAO, 2020). The first Peatland Pavilion took place at the 2021 United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP) 26 (IUCN, 2021). The UNFCCC includes peatlands (organic soils) in its Kyoto Protocol and the Paris Climate Agreement (IUCN, 2021). The Intergovernmental Panel on Climate Change (IPCC) has produced recommendations on national GHG reporting and accounting from drained, rewetted and burning organic soils (IPCC, 2014). Despite its importance, there is no uniform definition for peat or peatland (IPS, 2021). Peatland conservation is dependent on accurate quantification of peatland

extent, status, and carbon stock (Minasny et al., 2019; FAO, 2020). Current estimates of global and regional peatland carbon stock and extent are highly varied (Rieley and Page, 2016; Xu et al., 2018). Digital mapping using field observations combined with remotely sensed (RS) imagery and statistical models have been demonstrated to map peatlands more accurately and decrease this uncertainty (Minasny et al., 2019).

1.1.3 Remote Sensing

RS products and Geographical Information Systems (GIS) tools and techniques have been successfully utilised for multiple applications including LULC mapping (Mutanga and Kumar, 2019), peatland mapping (Draper et al., 2014; Dargie et al., 2017; DeLancey et al., 2019), vegetation (Huang et al., 2020), drought (AghaKouchak et al., 2021) and fire-related studies (Parks et al., 2018; Bar et al., 2020). The information obtained is used to aid scientists and policy-, and decision-makers (Opolot, 2013), and provides data from inaccessible and extensive areas (Mutanga and Kumar, 2019). The Geo Big Data problem is a view from geospatial and data scientists that require technologies and resources capable of handling large volumes of satellite imagery data (Shelestov et al., 2017). For example, the United States Geological Survey (USGS) has been collecting global earth observation data with frequent intervals since 1972 through the Landsat program (Masek et al., 2020). The data record will continue in future through the joint National Aeronautics and Space Administration (NASA)-USGS Landsat 9 mission which was launched in September 2021 (Gross et al., 2022). Open access to the entire Landsat archive was made available in 2008, however, this archive has been underutilized due to the challenges in collecting, storing, processing, and manipulating this multi-temporal and multi-spectral RS data (Shelestov et al.,

2017; Teluguntla et al., 2018). In addition, it is impractical to use common image processing software on desktop PC-based systems on data that span large geographic areas over five decades (Teluguntla et al., 2018; DeLancey et al., 2019).

Most recently, users have benefitted from the growing availability of high volume, freely accessible RS data and the development of cutting-edge, easy to use machine learning tools that have strong computing capacity (Shelestov et al., 2017; Mahdianpari et al., 2017, 2019; Amani et al., 2020). These advances offer new opportunities for applications at broader spatial and temporal scales, overcoming the limitations of existing methods and products in geospatial sciences (Mutanga and Kumar, 2019; Amani et al., 2020). The establishment of powerful cloud computing infrastructure has been made available through multiple platforms such as NASA Earth Exchange, Amazon's Web Services, Microsoft's Azure, and Google cloud platform to address the Geo Big Data problem (Mahdianpari et al., 2019). For instance, Google Earth Engine (GEE), a freely accessible, web-based cloud computing platform that contains numerous geospatial datasets and satellite imagery, allows for algorithm development and processes petabyte-scale data in good time (Hird et al., 2017).

1.2. Rationale

The Angolan Highlands are ecologically and hydrologically important (Van Wilgen et al., 2022), supporting peatland deposits (Goyder et al. 2018), and are an essential source water region for the Okavango Delta (Gumbricht et al., 2004) and southern Africa more broadly. Access to the region has been hampered by historical conflicts and persistent minefields, and as a result, it is under-studied (Taylor et al., 2018;

Goyder et al., 2018). Peatlands regulate global climate as undisturbed peatlands prevent further climate change (Rieley and Page, 2016). Mapping peatland extent has been documented to facilitate its preservation (FAO, 2020). Estimates of global peatland extent and carbon stock are inconsistent and have high variability (Minasny et al., 2019). This is evident in tropical zones where peatland deposits are comparatively less documented outside of those in Europe and North America (Page et al., 2007; 2011; Rieley and Page, 2016). To address this, the peatland extent in the Angolan Highlands warrants quantification. During periods of drought, peatlands have the potential to become net sources of carbon dioxide as aerobic respiration increases when soil moisture and the water table decrease (Fenner and Freeman, 2011; Lund et al., 2012; Jassey et al., 2018).

Having been well documented in the tropics, smouldering combustion of deep peat soil leads to peatland degradation (Page et al., 2002; Page and Hooijer, 2016; Rieley and Page, 2016), causing damage to the environment and human health (Marlier et al., 2013). Undisturbed peatlands are resistant to smouldering combustion due to waterlogging, burning of the surface vegetation does not result in peatland degradation (Vetrita and Cochrane, 2019). Peatland functioning is directly influenced by vegetation and hydrological conditions and is sensitive to drought and fire (Belyea and Malmer, 2004; Page et al., 2011). To address this, an assessment of both drought and the vegetation response to drought, peatland fire regimes and peatland response to fire necessitates investigation. The dynamics and of these peatlands have direct implications on the environment and communities of the Angolan Highlands and surrounding areas, and global climate more broadly.

1.3. Study Aim and Objectives

The primary aim of this research is to investigate dynamics relating to peatland extent, age and growth, and peatland response to drought and fire in the Angolan Highlands. To address the primary aim of this research, specific objectives of this research are:

1. To determine and map the extent of peatlands in the Angolan Highlands through machine learning.

2. To determine the drought history and the vegetation response to drought in the Angolan Highlands region through assessment of historical satellite data products.

3. To determine the contemporary fire regime of peatlands and peatland response to fire in the Angolan Highlands using fire and vegetation satellite data.

1.4. Structure of the Thesis

This thesis is divided into 9 chapters. Chapter 1: Introduction, provides the background, the rationale, and the study aim and objectives. Chapter 2: Study Region, provides a broad synopsis of the Angolan Highlands study region, including descriptions, maps and photographs of the topography, drainage characteristics, soils, vegetation, and contemporary climate. The NGOWP Lungui Bungu River transect took place in June 2022, none of the data collected are reported here, however, photographs obtained during the expedition are presented in Chapter 2. Chapter 3: Methodology, includes details regarding the use of GEE for RS data acquisition, and provides an overview of the NGOWP Lungui Bungu River transect. Chapters 4-7 represent each of the accepted journal papers. Chapter 8: General Discussion, explores three separate themes that cover the four research papers with reference to

academic literature, and includes a discussion of the main limitations of the research. Chapter 9: Conclusion, reflects on the extent to which the research aim and objectives have been achieved, the key findings and their significance, and possible avenues for future work. A comprehensive reference list follows the concluding chapter and contains all references from the journal papers and from the thesis chapters. In the case of chapters 4-7, a reference list is included according to the reference style of the respective journal the manuscript was submitted to. The supplementary files from each journal paper appear in the appendices at the end of the thesis rather than at the end of each journal paper.

CHAPTER 2: STUDY REGION

2.1 Introduction

In this chapter, a description of the World Wildlife Fund (WWF) ecoregions in Angola is presented, followed by the geographic location, topographical and drainage characteristics, soils and vegetation, and the contemporary climate of the study region.

Angola is located on the west-coast of south-central Africa, and the country spans 4°22'-18°02' S, 11°41'-24° 05' E (Huntley et al., 2019). Angola borders the Democratic Republic of the Congo (DRC) to the north, Zambia to the east, Namibia to the south, and the Atlantic Ocean to the west (Figure 2.1a). Angola covers a total surface area of 1,246,700 km^2 (Huntley et al., 2019), and has a population of 33,933,000 (2021), with a population density of 27.22 people per km^2 (World Bank, 2022). The WWF terrestrial ecoregions is a global data product that reflects the zonation of the Earth's terrestrial biodiversity, defining ecological units that share similar environmental conditions, species, and dynamics (Olson et al., 2001). The WWF terrestrial ecoregions showcase the diverse biogeographic and ecological conditions across the country (Figure 2.1b). Dominant ecoregions include the moist forest-savanna mosaics in the north, in the west a 1,600 km coastline contains scarp savanna and woodlands, and desert environments (Olson et al., 2001; Catarino et al., 2020). The miombo woodland ecoregion dominates the central and eastern parts of the country and the southern regions contain arid grasslands, savannas and woodlands along its 1,200 km border with Namibia (Olson et al., 2001; Catarino et al., 2020).

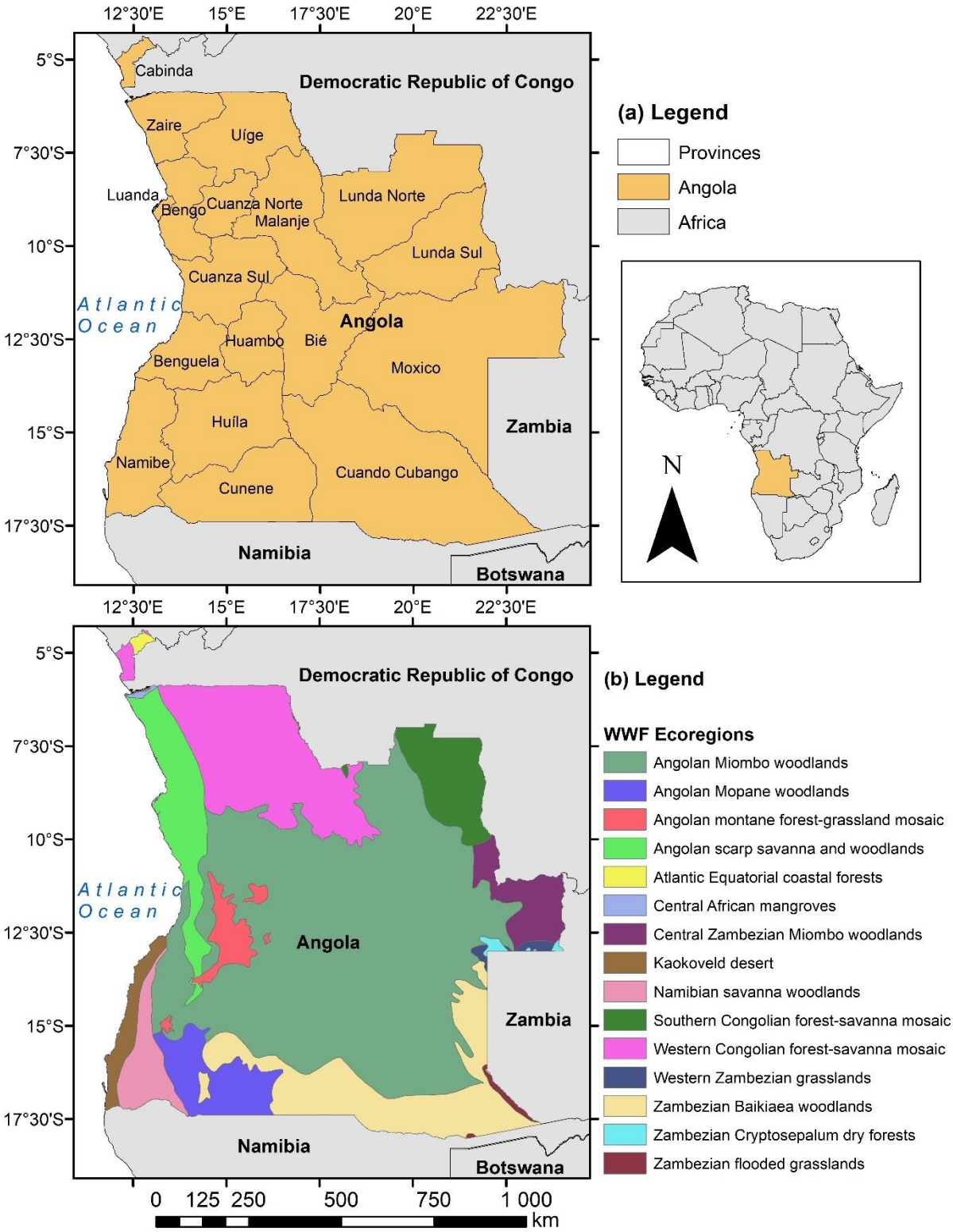

Figure 2.1. (a) Angola and its 18 provinces, and (b) the WWF ecoregions occurring in Angola (data from Olson et al., 2001).

2.2. Topography and drainage

Angola has a heterogeneous topography (Figure 2.2a). In the west, coastal lowlands below 200 m.asl occupy a band between 10–150 km in width and covers 5% of the country (Huntley, 2019). Adjacent to these lowlands, a mountainous escarpment rises to 1000 m.asl and covers 23% of Angola. The plateau is 1000-1500 m.asl and covers 65%, and areas above 1500 m.asl cover 7% of the country (Huntley, 2019). The study area is in the southeast of Angola (Figure 2.2b). This area covers an estimated 61,590 km^2 and spans 11°54′-13°54′ S, 18°05′-20°34′ E. The area has an elevation range of 1,117 m.asl in the southeast to 1,678 m.asl in the west.

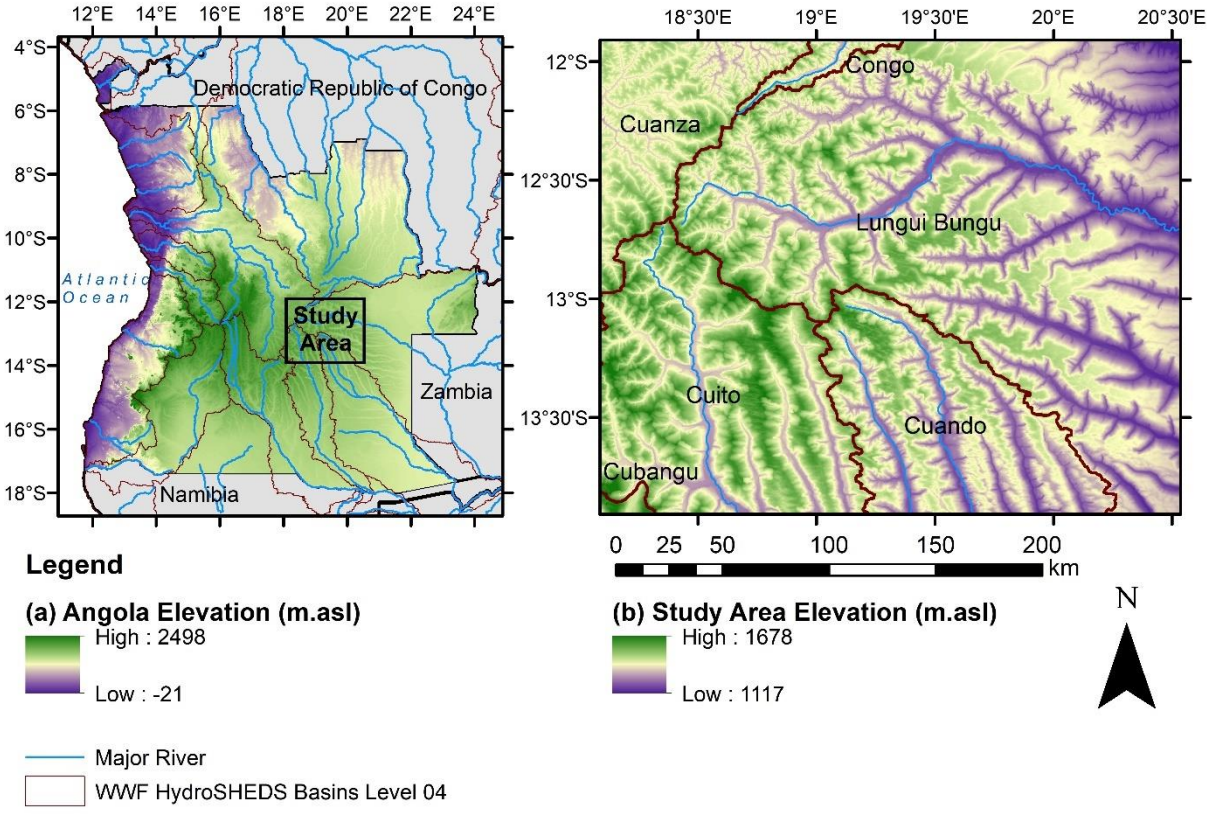

Figure 2.2. (a) Elevation of Angola depicting the extent of the study site, and (b) elevation of the study site including the WWF HydroSHEDS Basins Level 04 (data from Lehner and Grill, 2013) and major rivers.

The study area is situated within the Zambezi-Cubango Peneplain which is a vast generally flat area with rivers that meander down a gently dipping plateau (Huntley, 2019). The rivers originate from the northwest watershed with the Cuanza and Congo Basins and flow towards the southeast, eventually reaching the Namibian and Zambian borders (Figure 2.2). The study area forms part of the NGOWP core study region which includes the upper sections of both the Okavango and Zambezi watershed that originate in the Angolan Highlands. The NGOWP extracted peat cores at the Cuito, Cuanavale and Cuando source lakes and near the Lungui Bungu River source. The delineated study area is constrained to the mapped region of the journal paper presented in Chapter 5. This journal paper is a classification map of peatland extent based on the site locations of the peatland cores obtained during the NGOWP expeditions. For consistency, the same study area delineation was used in the journal papers presented in Chapter 6 and 7.

The drainage network forms part of the Angolan ‘water tower’, located in the central part of the country (Huntley, 2019). This water tower has nine river basins, of which seven are transnational (Huntley, 2019). The delineated study site includes six major river catchment boundaries: the Lungui Bungu which is a tributary of the Zambezi River and flows east into Zambia; the Cuando which flows south into Namibia, Botswana, Zambia, and Zimbabwe; the Cuito and Cubango which are part of the greater Okavango Catchment flowing southeast into Namibia and Botswana; the Cuanza which flows northwest covering large parts of Angola and the Congo which flows north into DRC. These rivers drain extensive and deep Kalahari sands, due to the filtration caused by the action of the sand layer, the rivers have high clarity and low nutrient levels (Huntley, 2019).

2.3 Soils and Vegetation

Over 75% of Angola is covered by two main soil groups, the sandy arenosols in the east and the ferralsols in the west and central plateaus of the country (Jones et al. 2013: Figure 2.3). The arenosols are the dominant soil group, covering more than half of Angola (Jones et al. 2013) and most of the study area. The arenosols form part of the Kalahari Basin, the largest body of aeolian sand on earth, extending for 2,500 km from the Cape to the Congo with a maximum width of 1,500 km (Garzanti et al., 2022). These sands cover almost half of Angola, hiding the underlying geology (Huntley, 2019). The quartz grains have no mineral nutrients, little accumulated organic matter, are infertile and have low water-holding capacity (Vainer et al., 2022). The Miombo woodlands ecoregion is particularly well adapted to the arenosols and ferralsols (Olson et al., 2001), and cover most of Angola (Huntley, 2019). The study area also contains alluvial fluvisols within drainage lines, these have high water-retaining capacity and organic content and are suitable for cultivation when not waterlogged (Jones et al. 2013; Huntley, 2019). In addition, gleysol clays are present and typically acidic, waterlogged and occasionally extensive within floodplains (Jones et al. 2013; Huntley, 2019).

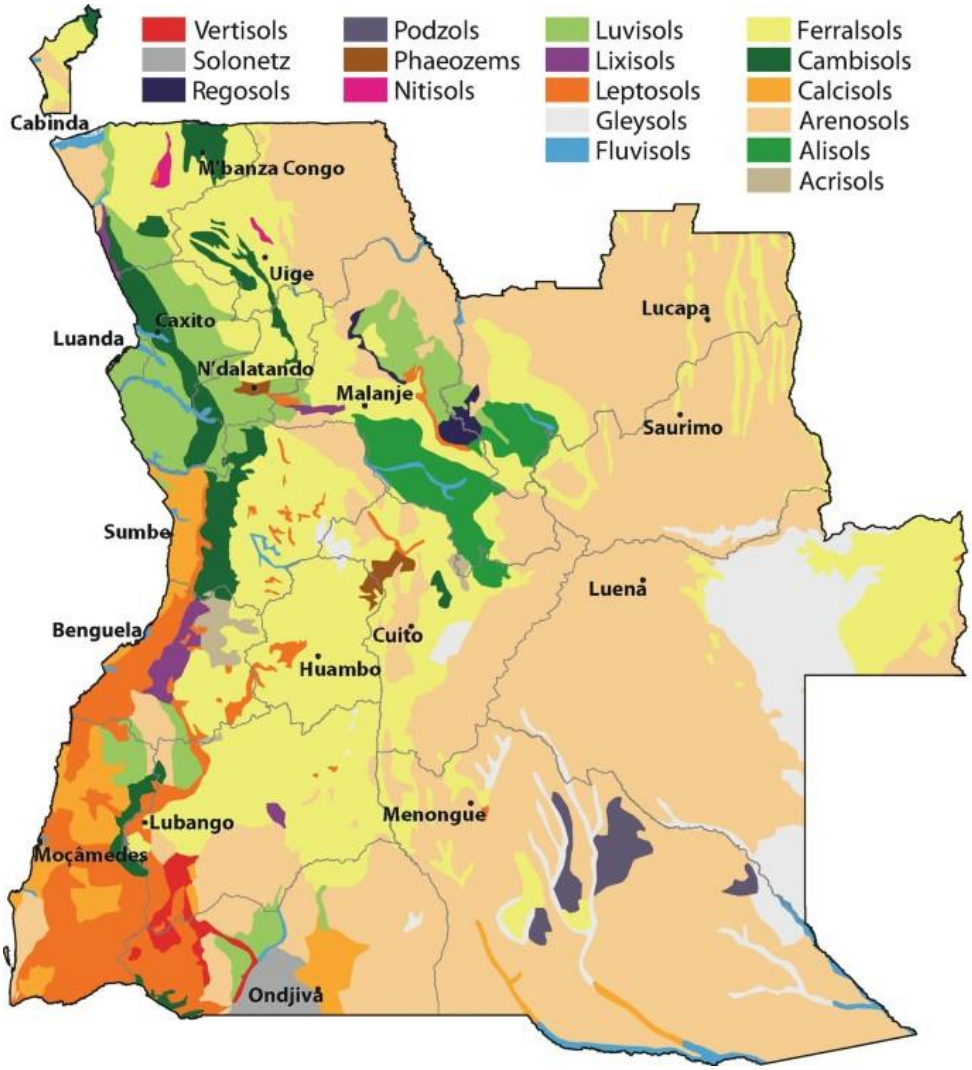

Figure 2.3. Soil map of Angola (from Jones et al. 2013).

Peat soil and peatland deposits were identified during exploratory surveys conducted by the NGOWP (Conradie et al., 2016; Goyder et al. 2018). Tropical peatland deposits have been defined as peatlands which are located between the Tropics of Cancer and Capricorn, including lowland and upland peatlands (Page et al., 2007, 2011). Tropical peatlands occur in Southeast Asia, the Caribbean and Central America, South America, and Africa (Rieley and Page, 2016). Africa has a diversity of peatland depositional environments that vary between sites, the majority of which are minerotrophic (groundwater fed), reflecting the dry climate of the continent (Grundling and Grootjans, 2016). Large ombrotrophic (rainwater fed) bogs exist in wet equatorial

regions such as the Congo Basin (Dargie et al., 2017; Davenport et al., 2020). The Angolan Highlands peatlands have formed in upland valleys. Similar peatland formation in upland valleys has also occurred in Rwanda (2,100 m.asl; Hategekimana and Twarabamenya, 2007), Lesotho (2400 m.asl; Trettin et al., 2008), and Burundi (1500 m.asl; Pajunen, 1996). In these high-altitude regions, the conditions for peat formation are comparable to temperate regions (Andriesse, 1988; Page et al., 2011).

The Angolan Highlands peatlands have diverse depositional environments, forming in lake margins (Figure 2.4a: Goyder et al., 2018), river floodplains (Figure 2.4b) and river terraces. These peatlands are minerotrophic; with evidence from field observations, drone (Figure 2.4c) and optical imagery, a distinct seep-line indicated by a narrow band of white sand exists parallel to higher ground immediately adjacent to the peatlands. This seep line is the inflow point of groundwater, the valleys are a gentle V-shape, and the peatlands all contour downwards towards the river.

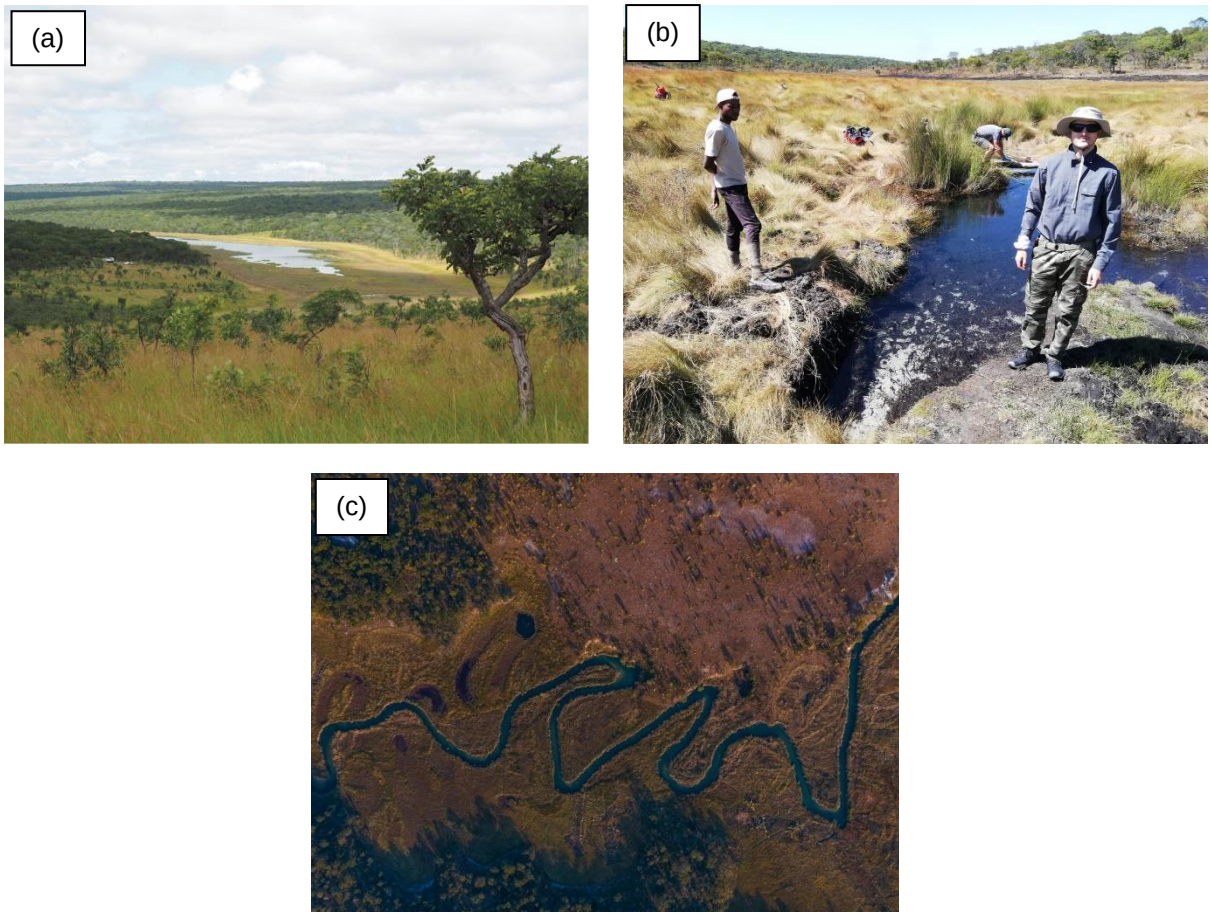

Figure 2.4. (a) The Cuito Source Lake, Moxico Province. Moist miombo woodland grows on the hillsides adjacent to the lake. Peatland surrounds the source lake, and a narrow band of grassland grows between the peatland and the miombo (from Goyder et al., 2018). Photograph D. Goyder. (b) Lungui Bungu River Source, Moxico Province. Small pool of acidic water filtering out of the surrounding peatland, miombo woodland surrounds the bowl-shaped peatland, and evidence of a recent fire in the background. Photograph R. von Brandis. (c) Lungui Bungu River, Moxico Province. The seep line indicated by a narrow band of white sand between the miombo and the floodplain environment, evidence of small-scale farming within the floodplain environment towards the south of the drone photograph. Photograph J. Guyten.

These peatlands are mostly waterlogged and dark in colour, forming in wet grasslands (Figure 2.5a). The rural communities practice small-scale subsistence agriculture which is reliant on rainfall and environmental conditions (Luetkemeier and Liehr, 2019). Communities often clear the miombo woodlands for cultivation, here the soils

are nutrient poor and dry due to the high sand content and high infiltration rates (Hunter and Crespo, 2019; Afonso et al., 2020). In addition, communities cultivate directly on the peatlands (Figure 2.5b), where it is common practice to cut drainage lines and burn the surface vegetation. These subsistence farmers produce low yields of corn, wheat, rice, potatoes, beans, cassava, sugarcane, peanuts, sunflower, sesame, and tobacco (Reyes et al., 2012). The woodlands and grasslands burn frequently (Figure 2.5c). Communities generally burn grasslands 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., 2022).

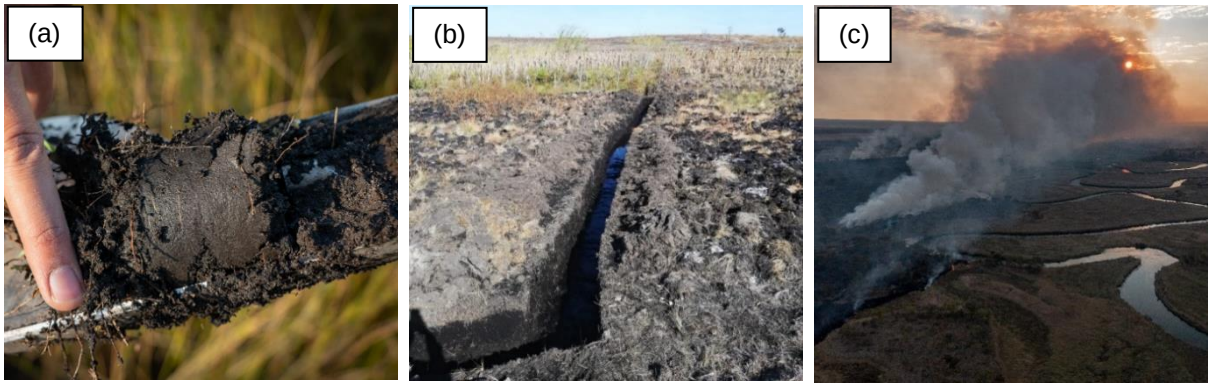

Figure 2.5. (a) Cut section of a peat soil sample extracted by M. Lourenco with a Russian corer. Photograph J. Guyton. (b) Burned (surface), cut, and drained peatland patch, cassava and lavender growing in the background near a small village along the Lungui Bungu River. Photograph M. Lourenco. (c) Drone photograph of a fire event along the Lungui Bungu River floodplain. Photograph J. Guyton.

The Angolan Highlands lie in the Angolan Miombo Woodland ecoregion which contains grasslands, woodlands, savannas and shrublands (Huntley et al., 2019). Barbosa (1970) described the vegetation as dense Zambesian and Congolian miombo woodland with “chanas” or geoxylic-rich grasslands. Within southern Africa, Angola is the least inventoried country for plants, and the east of the country has little to no geo-

referenced specimen data (Marshall et al., 2016). Goyder et al. (2018) provide a vegetation checklist and a baseline of plant diversity for the Angolan headwaters, a study that was part of the NGOWP series of expeditions. The species checklist (total of 417) is categorised into four main vegetation types: moist miombo woodlands, swamp forest, seasonally burned savannas, and wetlands (Goyder et al., 2018).

Miombo woodlands are tall, closed canopy woodlands dominated by trees in the genera *Brachystegia*, *Julbernardia*, and *Cryptosepalum* (Goyder et al., 2018; Van Wilgen et al., 2022). The miombo is extensive on the hillslopes and dominated by *Julbernardia.* Miombo growing on the plateau is dominated by *Cryptosepalum* which can form dense, closed canopy miombo forest rather than miombo woodland. In general, the miombo forests do not have a flammable grass undergrowth that is present in miombo woodland (Goyder et al., 2018). Large scale tree felling of the miombo vegetation has occurred within the Cubango catchment, by contrast, the vegetation in the Cuito catchment remains intact and homogeneous (Mendelsohn, 2019).

According to Goyder et al. (2018), swamp forest is rare and only occurs within Moxico Province, unlike the miombo woodlands and the seasonally burned savannas which are extensive. The seasonally burned savannas grow on highly leached Kalahari sand and are described as high-rainfall grasslands (Goyder et al., 2018). The habitat is fire-adapted and is dominated by grasses or geoxylic suffrutices, plants with large underground woody biomass and seasonal above-ground shoots. The factors controlling whether grasses or geoxylic suffrutices dominate are unclear. Maurin et al. (2014) argue fire is an important evolutionary driver, whereas Finckh et al. (2016)

provide evidence that frost plays a principal role, with cold air pooling in valley bottoms in the winter dry season and “burning” new shoots. Proximity to the water table limits growth of trees within these savannas (Goyder et al., 2018). Collins et al. (2019) classified these areas as open to sparse woodland and grasslands.

Historically, wetlands are under-sampled in Angola (Conradie et al., 2016). According to Goyder et al. (2018), wetlands are typically not botanically diverse, and do not host local endemics. The wide river valleys are characterised by extensive wet grasslands, peatlands, and ox-box lakes (Conradie et al., 2016). These seasonal floodplains along drainage lines are known locally as “chanas” (Van Wilgen et al., 2022) and more commonly referred to as “dambos” across tropical zones of Africa (Midgley and Engelbrecht, 2019; Skelton, 2019; Moore et al., 2022). The impeded drainage and high precipitation in the rainy season cause temporarily waterlogged soils in the valleys that support humid grassland borders with humic topsoil and dwarf shrubs and prevent the development of miombo woodland (Conradie et al., 2016). The river source lakes have peat accumulations at their margins and the river valleys also contain peat deposits (Goyder et al., 2018). Although described as not botanically diverse, the species checklist provided by Goyder et al., (2018) contains a total of 115 plant species identified in the wetland habitat of the Cuito catchment alone, 94 of which are associated with peat soils.

2.4 Contemporary Climate and Weather

The climate and weather of Angola is diverse, owing to topographic, atmospheric, and oceanic factors. There is a mean annual temperature difference of 4 °C (24.7 °C near the Equator versus 20.7 °C near the Tropic of Cancer), decreasing from north to south

(Huntley, 2019). Temperatures generally decrease with altitude, driven by the adiabatic lapse rate. There are major atmospheric systems over central and southern Africa that influence rainfall patterns across the country (Nicholson, 2018). The Inter-tropical Convergence Zone (ITCZ) is a belt of low pressure which circles the globe near the equator (Schneider et al., 2014). This is where the trade winds from the Southern and Northern Hemispheres converge, generating convective activity which drives moist conditions that are typical of the tropics (Nicholson, 2018).

Seasonal shifts in the location of the ITCZ affects the precipitation of many equatorial countries, resulting in distinct wet and dry seasons common in the tropics, rather than cold and warm seasons that occur in higher latitudes (Schneider et al., 2014; Nicholson, 2018). The ITCZ is on the equator during mid-autumn and mid-spring and migrates towards the Tropic of Cancer in the austral winter. The wet season starts when the ITCZ and the Congo Air Boundary shift over the north of Angola in early summer and reach the south of the country in late summer (Huntley, 2019). Mean annual rainfall is generally highest in the north and northeast (1680 mm/ year) and decreases towards the southwest (100 mm/year), high mean annual rainfall (1500 mm/ year) occurs in the high-altitude regions near Huambo Province (Figure 2.6; Cain, 2017).

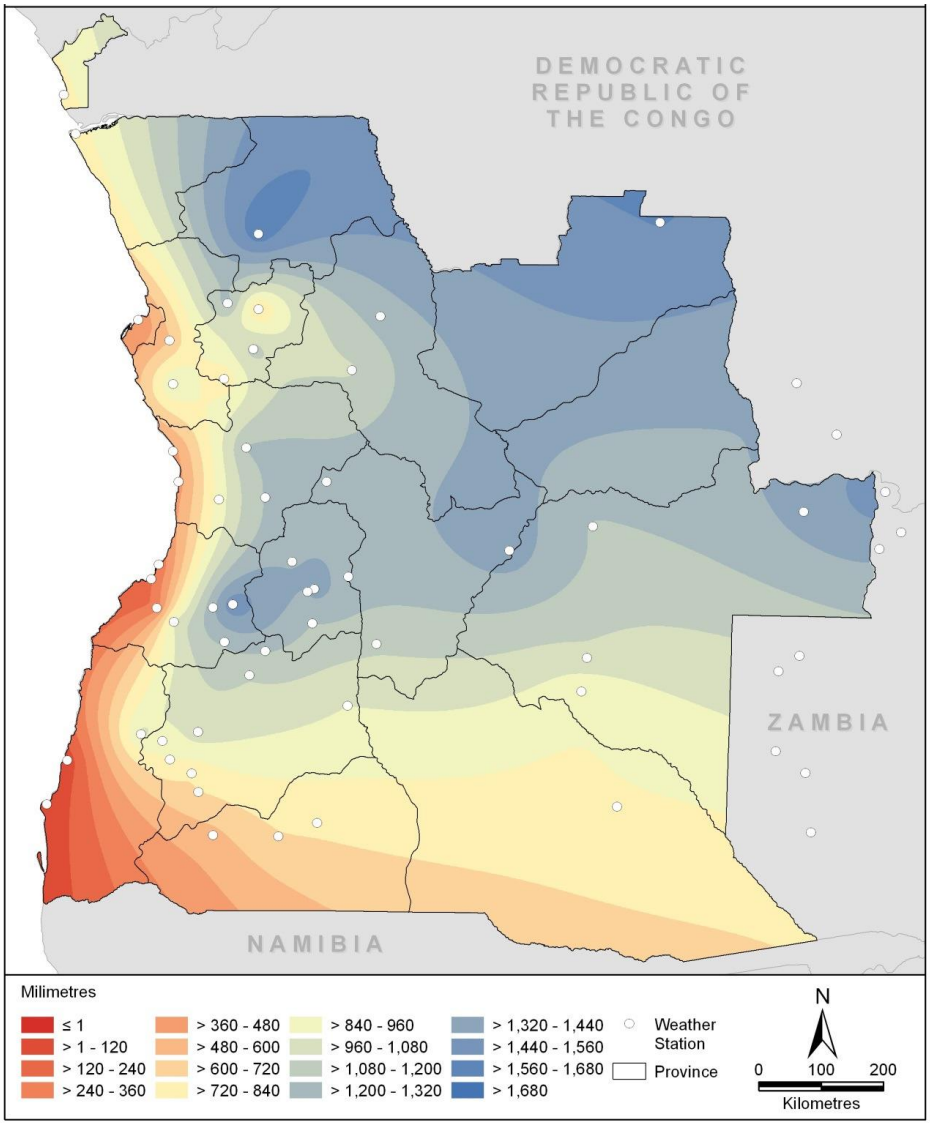

Figure 2.6. Mean annual rainfall in Angola (from Cain, 2017).

The climate is seasonal; hot and wet summers occur from October to May and mild to cool and dry winters occur from June to September (Huntley, 2019). The Köppen-Geiger climate classification (1980-2016) illustrates distinct climate zones in Angola (Figure 2.7; Beck et al., 2018). *Tropical, savanna (Aw)* covers large expanses of the central and northern parts of the country. The coastline is mostly arid, containing hot deserts *(BWh)* in the southwest (Beck et al., 2018). The Angola and Benguela Currents have a stabilising effect on the lower atmosphere and prevent cloud formation, resulting in the evolution of the Namib Desert (Lima et al., 2019). There are

two high-pressure systems that shift along with the ITCZ over the Atlantic Ocean and southern Africa: The Botswana Anticyclone and the South Atlantic Anticyclone. In winter, the anticyclones block the southward movement of moist air and prevent cloud formation. In summer, the anticyclones shift south and rainfall returns (Huntley, 2019). During the months spanning winter through to early summer, strong east-west winds are induced by the Botswana Anticyclone, picking up dust from the arid steppe and contributing to the Namib dunes (Huntley, 2019). The study area is characterized by *Tropical, savannah (Aw), Temperate, dry winter, hot summer (Cwa) and Temperate, dry winter, warm summer (Cwb)* climates which span the plateau (Beck et al., 2018).

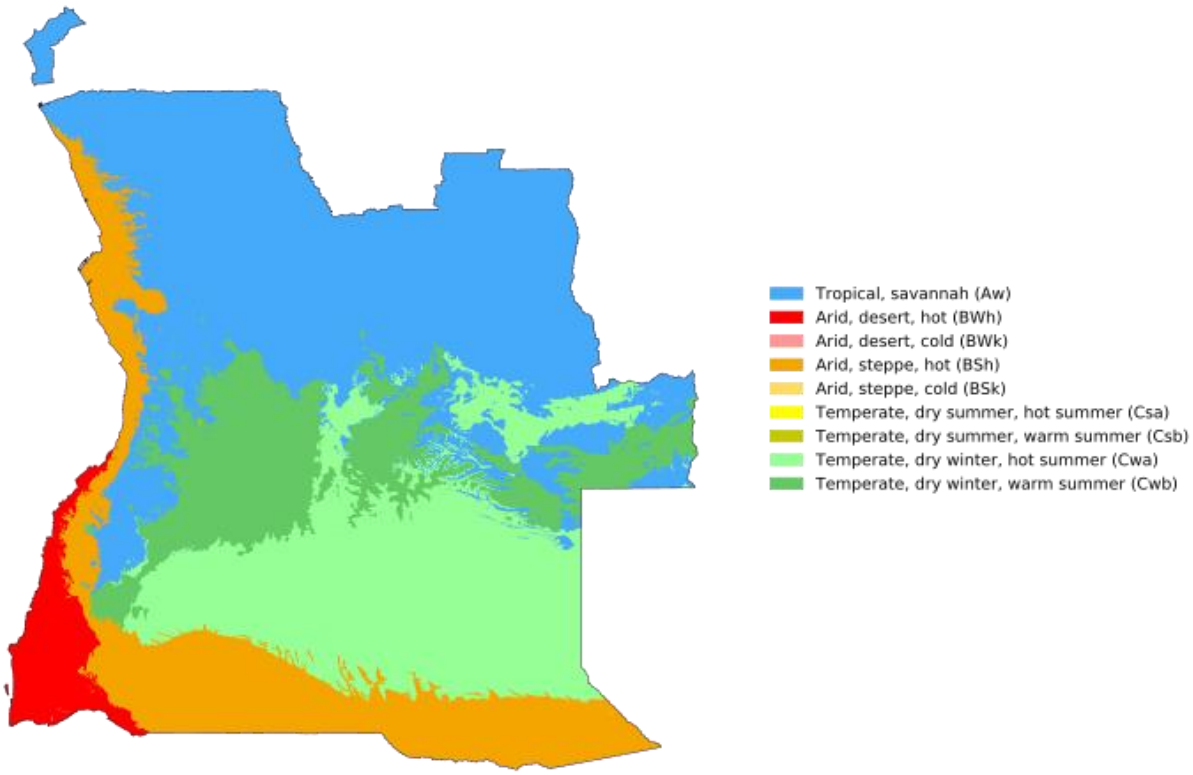

Figure 2.7. Köppen-Geiger climate classification map for Angola (1980-2016: adapted from Beck et al., 2018).

Studies that focus on Angola's climate have been hampered due to the collapse of an extensive network of metrological stations (Huntley, 2019). Between 1974 and 2010, Angola's climate network was reduced from 225 climatological posts (Silveira, 1967)

to zero, and 29 synoptic stations to 23 stations (Government of Angola, 2013). This is demonstrated in the study by Silveira (1967), a critical assessment of Angola's climate, that contained data from 184 stations across all 18 provinces. In addition, the study by Azevedo (1972), to map and classify the climatic regions, was based on this considerable national dataset, and still provides an accurate representation of Angolan bio-climatic systems (Huntley, 2019). In the case of Peel et al. (2007), a more recent study which provides an updated world map of the Köppen-Geiger climate classification, only five temperature and sixteen precipitation stations were used for Angola. Furthermore, records of extreme minimum temperatures and frost in Angola are absent (Zigelski et al. 2019). These factors, in combination with fires and herbivory, are important to the floristic diversity and composition of the country (Zigelski et al. 2019).

Due to the sporadic national meteorological station coverage and lack of reliable climatic data, this study makes use of climatic data obtained from RS products (Figure 2.8). Historical climate data from weather stations, specific to the study area, are unavailable. Distinct differences in precipitation and land surface temperatures occur within the study area. Historical precipitation and land surface temperature data for the region were collated from the GEE platform. Precipitation data were obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) 30+ year quasi-global rainfall dataset (Funk et al., 2015). CHIRPS synthesises 0.05° resolution satellite imagery with in-situ station data to create a gridded rainfall time series (Funk et al., 2015). Land surface temperature data were obtained from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Land Surface Temperature/ Emissivity 8-Day (MOD11A2) Version 6.1 product (Wan et al., 2021). This product

provides an average 8-day per-pixel land surface temperature and emissivity with a 1 km spatial resolution in a 1,200 by 1,200 km grid (Wan et al., 2021).

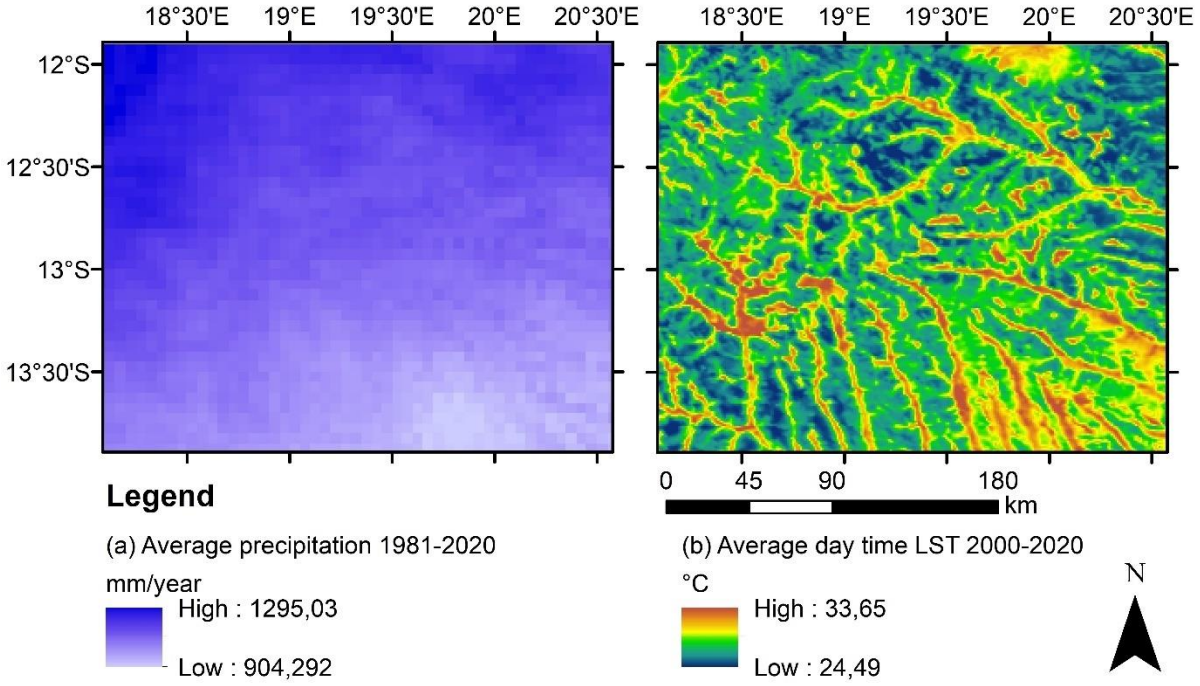

Figure 2.8. (a) Average precipitation (1981-2020) and (b) Average day time land surface temperature (2000-2020) for the delineated study area.

The mean annual precipitation over the study area is 1113 mm for the period 1981-01-01 to 2020-12-31. The highest annual precipitation (1295 mm) is recorded in the northwest and northeast regions of the study area (Figure 2.8a). Precipitation in the region is closely related to latitude and altitude. Both precipitation and altitude decrease towards the southeast where the mean annual precipitation is lowest (904 mm). The landscape has distinct topographical features dominated by river processes; high elevations exist adjacent to low lying river valleys. Land surface temperatures reflect these topographical features and are closely related to vegetation (Figure 2.8b). On average, miombo woodlands which grow on high elevations have cooler (24.5 °C)

land surface temperatures in comparison to the warmer valleys at lower elevations (33.6 °C).

2.5 Conclusion

Angola is a large country on the western coast of southern Africa. The important components of Angola's diverse ecoregions, topographical and drainage characteristics, soils, vegetation, and contemporary climate are detailed. These range from the Namib desert in the southwest, to the arid savannas of the coastal and southern areas, to the steep Angolan escarpment. Above the escarpment, high mountains contain Afromontane grasslands and forests. These mountainous areas are the source of several large rivers which drain into multiple neighbouring countries. Extensive miombo woodlands dominate the plateau and peneplains. Mean annual rainfall varies from below 100 mm in the southwest to over 1600 mm in the north of Angola. The precipitation and temperature across the country are closely linked to global and regional synoptic systems creating distinct wet and dry seasons. In addition, the topography and ocean currents have an influence on climate. Within the study area, the landscape contains distinct vegetation types, dominated by miombo woodlands. The peatlands which grow in the river valleys are controlled by multiple factors including groundwater, climate, topography, and vegetation. These peatlands provide extremely important ecosystem services as they purify water, limit river flow, provide fertile soil for agriculture, are a fuel source, and store carbon. Although the study area is rural, the strong anthropogenic influence on fire, wetland drainage and tree clearing are a threat to this region. This underscores the importance of investigating the peat dynamics within this area of Angola.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter provides a brief methodological background to the use of Google Earth Engine in remote sensing studies. In addition, an overview of the NGOWP Lungui Bungu River transect conducted in June 2022 is included. The specific analytical methods used in the analysis of peat extent, of drought and fire dynamics are detailed in each of the respective journal papers.

3.2 Remote Sensing

The Angolan Highlands are an extensive, understudied area that is largely inaccessible because of landmine presence following historic conflicts (Taylor et al., 2018; Goyder et al., 2018). Since the inception of the NGOWP in 2015, although conducting the most extensive scientific exploration across the region for 50 years (Conradie et al., 2016; Midgley and Engelbrecht, 2019), access to the region remains difficult and costly. RS has several advantages over traditional mapping and data collection approaches, field measurement techniques are limited by accessibility, scale, and cost, whereas remote sensing is quicker, more cost effective, and provides detailed information at a regional scale (Lees et al., 2018; Wu et al., 2014). Satellite data cover areas that are inaccessible and the repeat data collection enables effective environmental monitoring of dynamic phenomena such as precipitation, vegetation growth and fire (Mutanga and Kumar, 2019; Shiklomanov et al., 2019).

There are a wide range of RS datasets available that are often used in combination: multi-sensor approaches are highly useful for a variety of environmental monitoring research topics and have been used to identify and discriminate peatland from other wetland features (Hird et al., 2017; Mahdianpari et al., 2019; DeLancey et al., 2019). The availability of big data from earth observation products and the advances in machine learning, has provided further opportunities for new methods to aid in earth environmental monitoring (Gorelick et al., 2017; Amani et al., 2020; Yuan et al., 2020). Over the last decade, substantial progress in earth sciences has been observed, these new advances have outperformed traditional RS models with considerable improvement in performance (Tamiminia et al., 2020; Yuan et al., 2020).

3.3 Google Earth Engine

In recent years, following the significant advancement in sensors and increase in the number of RS datasets, multiple challenges to users working with big data have been created (Chi et al., 2016; Tamiminia et al., 2020). The challenges include big data computing, collaboration, and methodologies, as well as the appropriate data identification, deployment, representation, fusion, visualisation, and interpretation (Chi et al., 2016; Gorelick et al., 2017; Amani et al., 2020). The development of a safe, efficient, and advanced cloud computing platform was one of the most important requirements to provide a comprehensive solution to these challenges (Gorelick et al., 2017; Amani et al., 2020). Cloud computing platforms provide infrastructure, storage services, datasets, and software packages that enable the performance of a supercomputer on a standard device (Yuan et al., 2020; Amani et al., 2020).

GEE is a cloud computing platform launched by Google in 2010 (Tamiminia et al., 2020). GEE uses Google's computational infrastructure and has a large collection of open access satellite imagery and RS datasets that are constantly updated (Gorelick et al., 2017; DeLancey et al., 2019; Tamiminia et al., 2020). GEE is freely accessible and the most popular big data processing platform (Amani et al., 2020). Users can access GEE through an internet-based Application Programming Interface (API) and a web-based interactive development environment (Mahdianpari et al., 2019). Furthermore, users do not need to download the large datasets and GEE has an automatic parallel processing and fast computational platform that effectively deals with big data at a petabyte scale (Gorelick et al., 2017; Amani et al., 2020). In addition to its computing and storage capacity, several well-known machine learning algorithms have been implemented, and users are able to develop and share their own algorithms easily (Chi et al., 2016; Tamiminia et al., 2020). The data outputs and map exports are complimentary to existing RS and GIS software packages (Chi et al., 2016; DeLancey et al., 2019).

Considering the trends of GEE use in research over the recent past, it is projected that users will more frequently use GEE as the main cloud computing service in future (Tamiminia et al., 2020). In this study, GEE was used as the primary platform for RS data extraction and storage and used in some analytical approaches. Map visualisations and calculations were performed using ArcMap software. Sample GEE scripts were obtained from the dedicated GEE developers guide and API Javascript tutorials. These were revised for the study site and specific date ranges for each journal paper chapter. During this study, an ethics clearance was not needed as the data collected was solely obtained from freely accessible RS datasets on GEE.

3.4 NGOWP Lungui Bungu River expedition

To ensure long-term, sustainable protection for the Okavango watershed, the NGOWP has been conducting surveys, gathering scientific data concerning the river systems and collaborating with local communities, non-government organisations and the governments of Angola, Namibia, and Botswana (National Geographic Society, 2022). Since 2015, the NGOWP have completed multiple expeditions, performing river transects across the length of the catchment from the source waters in the Angolan Highlands to the Makgadikgadi Pan in Botswana (National Geographic Society, 2022). The NGOWP core study region has since expanded to other major river basins originating from the Angolan Highlands including the Zambezi catchment. The first NGOWP expedition conducted in Angola following the COVID-19 global pandemic took place in June 2022. The transect for this field work as part of the PhD, started at the Lungui Bungu River source, and continued east, along the river, until the Angola-Zambia border. The Lungui Bungu River is a major tributary to the Zambezi River.

Prior to this expedition, observations of the landscape were limited to RS satellite datasets as this was the candidates first visit to the study area. In previous NGOWP expeditions, peat cores were collected on the river floodplain near the Lungui Bungu River source. Following Accelerator Mass Spectrometry (AMS) radiocarbon dating, important data regarding peatland formation was obtained. With this background knowledge, a peatland classification map for the region was generated prior to this expedition. The Lungui Bungu River transect provided an opportunity to validate this peatland classification. In addition, observations of the peatland landscape revealed further insight of the threats to these deposits and provided additional verified peatland

extent data that was used in Chapter 7. The specific details regarding the data and methodologies used are mentioned in each journal paper chapter.

The principal aim of this expedition was to conduct the first known scientific exploration of the length of the Lungui-Bungu River. Selected outcomes and achievements of the expedition are described in this thesis. However, the primary results of this expedition fell outside of the scope of this work and therefore do not appear in this thesis. Importantly, this provided the opportunity to visit the study site and to understand the context in which the RS work was done. Outcomes specific to the peatlands include an additional 17 core samples of peat soil that were collected along the length of the river. The cores were collected using a Russian peat corer and have been radiocarbon dated at the iThemba LABS. In addition, water quality data using a multiparameter probe and water discharge using an acoustic doppler current profiler were collected every 10 km along the river length. Biodiversity counts, evidence of human interaction with the river (for example, fishing nets) and fire events near the river were recorded along the transect. River invertebrate biodiversity assessments were performed every 30 km along the river.

CHAPTER 4: PEAT DEFINITIONS: A CRITICAL REVIEW

4.1 Brief synopsis

This critical review presents a brief history on peatland definitions through time. The review highlights the current state and discrepancies between definitions concerning peatland nomenclature and classifications. Multiple disparate definitions are presented with specific focus on the criteria concerning minimum depth, organic carbon, organic matter, and ash content. This study presents a new definition for peat, the motivation behind this definition is for conservation purposes and from the perspective of climate science, preservation, and carbon accounting. This is an important contribution as the literature concerning peat and peatland definitions is inconsistent, causing multiple implications, including the quantification of global peatland carbon stock.

Author contributions:

Contributor role	**Author contribution**
Conceptualisation	Lourenco M, Fitchett JM, and Woodborne S
Methodology	Lourenco M, Fitchett JM, and Woodborne S
Validation	Lourenco M
Formal analysis	Lourenco M
Investigation	Lourenco M
Resources	Lourenco M
Data curation	Lourenco M
Writing – the original draft preparation	Lourenco M
Writing – review and editing	Lourenco M, Fitchett JM, and Woodborne S
Visualisation	Lourenco M
Supervision	Fitchett JM and Woodborne S
Project leaders	Fitchett JM and Woodborne S

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Lourenco M – 70%

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Peat definitions: A critical review

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Abstract

Peatlands are carbon-rich ecosystems that comprise the largest terrestrial carbon store. Peatland preservation has been acknowledged on the global scale as a key nature-based component in addressing climate change. Despite their importance, there is no globally recognised definitions for peat or peatland, which influences efforts in quantifying global peat carbon stocks. We present a critical review on peatland definitions, including peat nomenclature and changing criteria for peatland classification through time. We focus on two important criteria: the minimum depth of the surface organic layer and the minimum percentage of organic carbon. We highlight the disparity between definitions, peatland nomenclature and peatland classifications. It is challenging to determine whether one definition should take precedence over another, even when considering the most common criteria. We propose that future peatland definitions focus on carbon storage and potential greenhouse gas emissions. This involves four physical and chemical characteristics of the peatland deposit: (1) Peatland extent, (2) peat thickness, (3) peat carbon content and (4) peat bulk density (volumetric carbon content). The growth dynamics and carbon flux of the peatland deposit should also become a routine part of inventories. In future, international technical agencies and experts can advise on the standardisation of concept definitions and methods, these must focus on the preservation of peatlands from the perspective of climate science.

Keywords

carbon, greenhouse gases, preservation, wetland, moor

Introduction

Peatlands are estimated to cover 3% of the global land surface and are distributed across almost every country on the planet (Page et al., 2011; Xu et al., 2018). Peatlands are terrestrial wetland ecosystems that facilitate the growth of peat (Dargie et al., 2017). Peat is a type of organic-rich soil that consists of partially decomposed organic matter, derived mostly from plant material, which has accumulated under conditions of waterlogging, oxygen and nutrient deficiency, and high acidity

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(International Peatland Society: IPS, 2021). Peatlands provide multiple ecosystem services that are significant to the Sustainable Development Goals (Food and Agriculture Organization: FAO, 2020), most important with respect to regulation of global climate as peatlands are the largest natural terrestrial carbon store (Rieley and Page, 2016; Xu et al., 2018). The collective global effort to reduce anthropogenic impact on climate has placed greater importance on vulnerable natural carbon sinks (Friedlingstein et al., 2019; Minasny et al., 2019).

Peat and peatlands have been recognised on the global scale as essential to several international conventions and policies that focus on protecting habitats, biodiversity, carbon sinks and reducing greenhouse gas (GHG) emissions (FAO, 2020). The first Peatland Pavilion took place at the 2021 United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP) 26, highlighting the importance of global peatlands for climate, people and the planet – peatlands being a key nature-based solution to climate change (International Union for Conservation of Nature: IUCN, 2021). The UNFCCC included peatlands in the 1997 Kyoto Protocol, the 2015 Paris Climate Agreement, and national GHG accounting and reporting (FAO, 2020). The Intergovernmental Panel on Climate Change (IPCC) produced guidance on reporting on GHG emissions from drained, re-wetted and burning organic soils (IPCC, 2014) that must be transparent with respect to measurement and verification (FAO, 2020). Measurement involves quantifying the different physical and chemical properties of the peat (Joosten et al., 2017a), but an underlying assumption is that there is a common understanding of what constitutes peat. Research is continuously contributing to the refinement of definitions, but further research is needed over all applications (Hiraishi et al., 2014; FAO, 2020; IPS, 2021). This is of particular concern in regions across Africa where land use change threatens peatland conservation (Murdiyarso et al., 2019; Lupascu and Wijedasa, 2021). Despite the importance of peatlands, there is no globally recognised definition for peat or peatland (IPS, 2021).

At the start of the 21st century, international peatland terminology was in a state of confusion (Joosten and Clarke, 2002). Broad definitions of both peat and peatland that are widely cited: 'peat is sedentarily accumulated material consisting of at least 30% (dry mass) of dead organic material. A peatland is an area with or without vegetation with a naturally accumulated peat layer at the surface' (Joosten and Clarke, 2002: 24) and '"peatlands" are areas with a minimum peat depth of 30 cm' (Joosten and Clarke, 2002: 42). Despite wide use for these definitions, researchers, national authorities and peatland interest groups have continued to use a range of definitions for peat and peatland, some of which are developed internally (Tanneberger et al., 2017; Wu et al., 2017; Xu et al., 2018). Definitions also vary across scientific discipline (IPS, 2021).

Contradictions in definitions most frequently relate to the minimum depth of the soil surface organic layer and the minimum percentage of organic carbon (Tanneberger et al., 2017; Xu et al., 2018; IPS, 2021). This is problematic as it affects estimates of the extent of peatland, and determinations of the volume and carbon content (Joosten, 2010; IPS, 2021). These have implications for national and continental peatland inventories that are combined to estimate global peatland coverage and carbon stocks (Tanneberger et al., 2017; Xu et al., 2018). The FAO (2020) highlights the range of country-specific definitions, recommending that international technical agencies and experts in peatland science advise on the standardisation of concepts, definitions and methods. In this study, we provide a critical review of the development of peat definitions, and the current state of definitions including nomenclature and classifications and propose recommendations regarding peat definitions that would benefit international peat science.

Peatland definitions: A brief history

There is a distinction between peatland classifications and peatland definitions. Peatland classification refers to the act of assigning peat to classes (groups or orders) according to common relations or characteristics and then assessing the distribution of classes (Lindsay, 2016). Peat definitions refer to semantics, a statement of the meaning of the word peat that is based on specific defining criteria and thresholds regarding the physical and chemical properties of the soil layer (Joosten and Clarke, 2002).

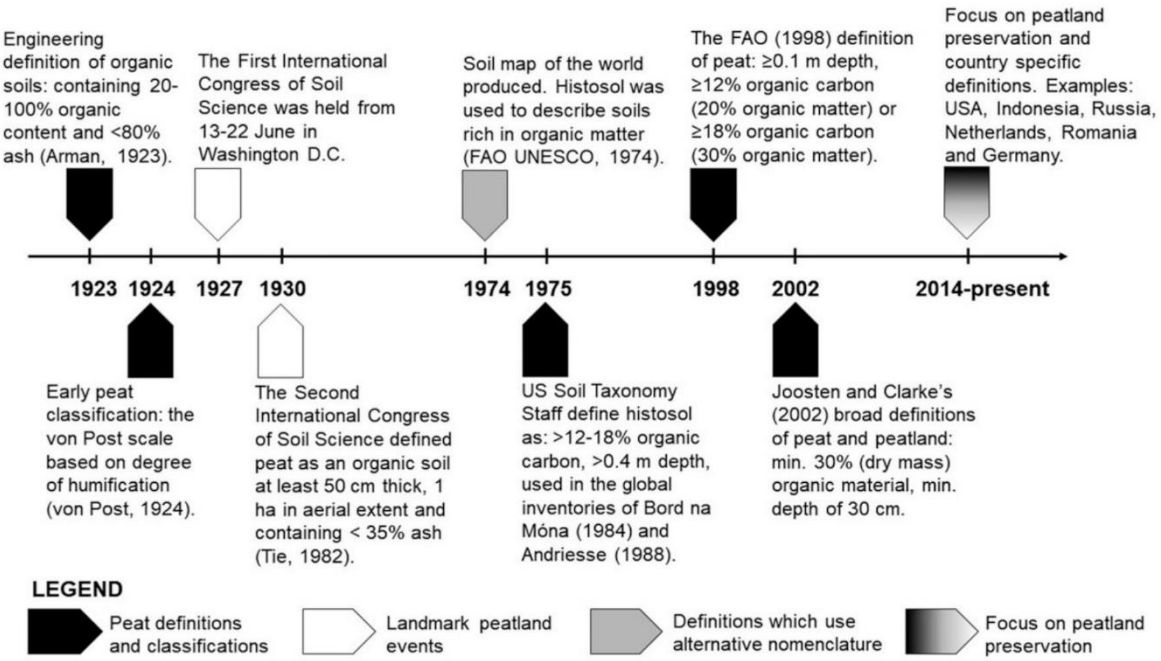

Figure 1. Development of peat definitions through time.

Peat is mentioned during the Roman times, as during the 12th and 13th century it was an important energy source across Europe (Joosten et al., 2017a). Peat is still used as a fuel source, particularly in Belarus, Estonia, Finland, Indonesia, Ireland, the Russian Federation and Sweden (World Energy Council, 2013). The oldest systematic classification of bogs in written literature dates to 1652 (Joosten et al., 2017a). In the early 20th century, Arman (1923) defined organic soils as soils containing 20–100% organic content and <80% ash content from an engineering perspective (Figure 1). The First International Congress of Soil Science was held from 13 to 22 June 1927 in Washington D.C. and was a landmark event in the development of soil science (Shull and Thone, 1927). It was followed in 1930, by the Second International Congress of Soil Science where peat was defined as an organic soil at least 50 cm thick, 1 ha in aerial extent and containing <35% ash (Tie, 1982). This definition included extent as a defining parameter, but an extent threshold has rarely been used as a criterion in updated definitions or applications.

An important early development in peatland science and classification was the von Post scale (Von Post, 1924). The von Post scale classifies peat on its fibre content, and the related degree of humification or decomposition (Zulkifley et al., 2013). Although widely cited, the von Post scale remains a subjective and qualitative measure of decomposition (Grover and Baldock, 2013). Solid matter volume, bulk density and dry density have been used as proxies for decomposition and have the benefits of being objective, quantitative and easy to measure (Bloemen, 1983; Grover and Baldock, 2013). Ash content was used to differentiate between peat and muck (Davis, 1946), and continues to be used as a defining criterion in more recent definitions (Osaki et al., 2016)

In the FAO – United Nations Educational, Scientific and Cultural Organization (UNESCO) 1974 Soil map of the world, histosol was used to describe soils rich in organic matter (FAO UNESCO, 1974), and was used in parallel with other peat nomenclature used throughout the world: 'Moor peats' (Australia); 'Organic soils' (Canada.); 'Sols hydromorphes

organiques' (France.); 'Moorböden' (Germany.); 'Histosols' (USA) and 'Bog soils' (USSR: FAO UNESCO, 1974) (Supplement Material). This definition acknowledged the different regional nomenclatures for peat and introduced the histosol as a defining concept. Although the definition made use of the term histosol, it did not include details regarding organic carbon content as stipulated in the definition for histosol provided by the US Soil Taxonomy Staff of >12–18% organic carbon (US Science and Education Administration, 1975). The FAO UNESCO (1974) definition included only depth and bulk density (>0.4 m, or >0.6 m if the organic material consists of sphagnum or moss or if it has a bulk density of less than 0.1) and is one of the very few definitions that includes bulk density as a defining criterion.

Defining histosol as >12–18% organic carbon, >0.4 m depth (United States Science and Education Administration, 1975), was the same as that used in the global inventories of Bord na Móna (1984) and Andriesse (1988). The definition for organic soil deriving from soil science from the FAO (1998) differs from this only with regards to depth (≥0.1 m). The FAO (1998) definition appreciates both organic carbon and organic matter percentage in its defining criteria. Broadly speaking, the definitions between Joosten and Clarke (2002) and FAO (1998) concur in terms of organic matter percentage, but differ in terms of soil depth, with Joosten and Clarke (2002) requiring >0.3 m, and FAO (1998) requiring ≥0.1 m. The definition of histosol prior to the peat definition proposed by Joosten and Clarke (2002) meant that older peatland inventories are based on the histosol definition (Montanarella et al., 2006; Xu et al., 2018).

Over the last decade, the focus of the literature has steered in the direction of preservation of peatlands (Finlayson and Milton, 2018; Rieley and Page, 2016; FAO, 2020). According to Minasny et al. (2019), establishing a national definition for peat, including minimum thickness, is important in defining mapping methodologies. Recent examples of national definitions for peat include countries such as the USA (United States Soil Taxonomy Staff, 2014), Indonesia (Osaki et al., 2016), the Russian Federation, Netherlands, and Romania (Tanneberger et al., 2017), and Germany (Schulz et al., 2019). In the IPCC 2013 Wetlands Supplement, it is "good practice" that when a country uses another definition of organic soil in accordance with its national circumstances, the concept (and its possible subdivisions) is clearly defined, and that the definition is applied consistently across the entire national land area and over time (IPCC, 2014).

Defining peatlands: current state and discrepancies

Peatland nomenclature

Since the inception of peatland science, efforts towards a common typology and terminology have been a central aim (Joosten et al., 2017b). This is hampered by a wide range of ecosystems and environmental factors including source and type of water, climate, depositional setting, nutrient availability, vegetation cover and peatland use (Wüst et al., 2003; Huat et al., 2011; Minasny et al., 2019). Nomenclature used to define peat and peatlands is therefore highly varied (Table 1). Ecosystems include forested and non-forested areas, temperate, tropical and high-altitude environments that facilitate the growth of peat in settings such as swamps, marshes, sumps, wetlands, muskegs, lowlands and sloughs (Page et al., 2011; Rieley and Page, 2016; Finlayson and Milton, 2018). Common peatland nomenclature from the English language includes peatland, wetland, histosol, organic soil, mire, moor, bog, fen and suo (Finlayson and Milton, 2018; Tanneberger et al., 2017; Joosten and Clarke, 2002), which are not easily translated to different languages as the landscapes, people, traditions and perspectives are different in each country (Joosten et al., 2017a).

In any scientific discipline, when terms are translated, difficulties occur as different languages often do not have identical concepts, and this is especially true for peatland definitions (Joosten et al., 2017a; Tanneberger et al., 2017). Joosten et al. (2017a) present an updated review on peatland nomenclature and terms used in Europe, but do not engage exhaustively on terminology used elsewhere. Peatland literature in different languages is extensive (Joosten, 2004; Joosten et al., 2017b; Osaki et al., 2016; Tanneberger et al., 2017). Confusion even exists

Table 1. Peat nomenclature used in definitions.

Category	Peat nomenclature (English language) used in definitions
Common names	Peat[1-35], peatland[1-35], true peat[13,36], true bog[37], eccentric bog[37], histosol[3,4,12,13,20,21,22,25,32], organic soil[1,3,18,32,38], fen[13,19,22,32], mire[12,13,22], bog[3,4,12,13,15,16,19,21,32], blanket bog[13,15,16,17,22,36], raised bog[3,4,13,15,16,17,22,33,36], quagmire[22,42], muskeg[12,22], moors[3,4,13,21,22,42], morass[42], suo[22], mud[22,33,42], muck[2,4,5,6,21,23]
By depositional setting	Swamp[22,42], swampland[22,42], marsh[13,39,42], marshland[13,33,39,42], wetland[22,40,41], lowlands[40,41], everglade[40,41]
Related to vegetation	Peat moss[3,22,36], *Sphagnum* moss[3,22]

Notes to Table 1: [1]2nd International congress of soil science 1930 cited by Tie (1982), [2]Davis (1946), [3]FAO UNESCO (1974), [4]US Science and Education Administration (1975), [5]Kivinen et al. (1979), [6]Kearns et al. (1982), [7]ASTM cited by Purnomo et al. (2012), [8]Mankinen and Gelfer (1982), [9]Andrejko et al. (1983), [10]Landva et al. (1983), [11]Jarret (1983), [12]Bord na Móna (1987), [13]Andriesse (1988), [14]Moris (1989), [15]Soil Survey of Ireland cited by Cruickshank and Tomlinson (1990), [16]Soil Survey of England and Wales cited by Cruickshank and Tomlinson (1990), [17]Soil Survey of Scotland cited by Burton (1996), [18]FAO UNESCO (1997), [19]Canadian Agricultural Services Coordinating Committee (1998), [20]FAO (1998), [21]Baillie (2001), [22]Joosten and Clarke (2002), [23]Wüst et al. (2003), [24]Huat et al. (2011), [25]US Soil Taxonomy staff (2014), [26]Indonesian Ministry of agriculture cited in Purnomo et al. (2012), [27]Osaki et al. (2016), [28]The Russian Federation cited in Tanneberger et al. (2017), [29]Netherlands cited in Tanneberger et al. (2017), [30]Romania cited in Tanneberger et al. (2017), [31]Schulz et al. (2019), [32]Joint Research Centre cited in Panagos et al. (2020), [33]Lindsay (1995), [34]Finlayson and Milton (2016), [35]Tanneberger et al. (2017), [36]American Society for Testing and Materials (ASTM: 1969), [37]Davis and Anderson (1991), [38]Arman (1923), [39]Godwin (1941), [40]Page et al. (2011), [41]Rieley and Page (2016), [42]Haslam (2003).

within the border of a single country or within one language, as the meaning of the word may change depending on the discipline or historical context (Tanneberger et al., 2017; Xu et al., 2018). For example, in the United Kingdom, Farm Bog in London is a fen and Holme Fen in Cambridgeshire is a bog, and terms such as 'basin bog' and 'valley bog' would more accurately be termed 'basin fen' and 'valley fen' for groundwater-fed peatlands (Lindsay, 2016). Andriesse (1988) mention 'true peat' has 100% organic matter, 'true peat' is defined by the American Society for Testing and Materials (ASTM) as organic material of plant origin, excluding coal, with at least 75% organic matter (ASTM, 1969). The use of the term 'true peat' or 'true bog' as defined by Davis and Anderson (1991) may also be misleading if used in the wrong context and should perhaps be avoided as it invites other terms such as 'false peat' or 'untrue peat'.

Peatland classifications

Numerous classification systems based on peatland characteristics have developed over time (Table 2), and there is still no single complete or definitive classification system (Lindsay, 2016). Peatlands were historically classified from an economic and land exploitation perspective (Joosten et al., 2017b). Following the progress of ecology, peatlands were classified as ecosystems and the total landscape was considered (Lindsay, 1995; Joosten et al., 2017b). Peatland classifications incorporate soil science, biodiversity value and carbon storage perspectives (Lindsay, 2016), owing to the multitude of peatland interest groups including, among others: scientists, farmers, foresters, peat extractors, land use planners and conservationists (Lindsay, 1995; International Peatland society IPS, 2021). Classification systems are determined by their purpose, therefore the classes created for different disciplines will differ (Joosten et al., 2017b) (Supplement Material).

Classification may be based on the properties of the peat, such as thickness, extent, pH, carbon content, ash content, water table depth or degree of humification (Table 2; Huat et al., 2011). The most common way to distinguish these properties is to express differences on a numerical scale (Huat et al., 2011). As there are several possible defining properties, and each with its own continuous scale, the

Table 2. Basis for peatland classification systems.

Peatland classification based on	Classes
Water source	Ombrogenous[1], groundwater peat[1], raised bog[1], topogenous[2], soligenous[2]
Theoretical framework regarding the source of waterlogging and behaviour of the water supply (hydrogenetic typology)	Geogenous fen[3], ombrogenous bog[3] soligenous bog[3], lithogenous bog[3], thalassogenous bog[3]
Degree of humification	Decomposition ranges from H1–H10, H1: Completely undecomposed, H10: Completely decomposed[4]. Fibric[5,6], hemic[5,6], sapric[5,6]
Nutrient level	Oligotrophic acid[3,8], mesotrophic acid[3,8], mesotrophic subnuetral[3,8], mesotrophic calcareous[3,8], eutrophic[3,8], salt influence[3,8]
Peat forming habitat	Fen[9,10], bog[9,10], watershed mire[11], valley side mire[11], spur mire[11], saddle mire[11], ridge-raised bog[10,11,12], saddle/ watershed intermediate bog[10,11]
Mineral soil water boundary	Ombrotrophic[13], minerotrophic[13]
Hydromorphological typology	Raised blanket bog[11,14], ridge-raised bogs[11,14]
Hierarchical classification of mire systems (Tope system)	Tope system ranges from microtope to nanotope and includes vegetation[15,16,17]
Water chemistry and hydromorphology	Ecological mire types[18], hydrological mire types[18]
Organic content	Peat[7,19-27], muck[7,19,20,22,25,27,29], organic soil[22,24,26,28]
Ash content	Peat[7,19-27], muck[7,19,20,22,25,27,29], organic soil[7,22,24,26,28]

Notes to Table 2: [1]Weber (1902), [2]von Post and Granlund (1926), [3]Joosten and Clarke (2002), [4]Von Post (1924), [5]Soil Survey Staff (1990), [6]Esterle (1990), [7]Wüst et al. (2003), [8]Succow (1988), [9]Tansley (1939), [10]Godwin (1941), [11]Lindsay (1995), [12]Steiner (2005), [13]Du Rietz (1954), [14]Moore and Bellamy (1974), [15]Ivanov (1981), [16]Wells and Zoltai (1985), [17]Moen (1985), [18]Succow and Jeschke (1990), [19]Davis (1946), [20]Kearns et al. (1982), [21]Mankinen and Gelfer (1982), [22]ASTM 1982 cited in Purnomo et al. (2012), [23]Andrejko et al. (1983), [24]Landva et al. (1983), [25]Jarrett (1983), [26]CSSC (1987), [27]Moris (1989), [28]Arman (1923), [29]Kivinen (1963).

number of peatland types could be countless without variable associations (Joosten et al., 2017b). For example, Wüst et al. (2003) propose a classification system for tropical organic-rich peatland deposits, focusing on the use of ash and organic content, with 11 different classifications emerging on the basis of these alone. Peatland classification according to properties such as ash and organic content are only measurable by laboratory techniques. By contrast, Lindsay (2016) provides a review on classifications that focus on peatlands as ecosystems, including classifications based on peatland vegetation, chemistry, source water, hydromorphology and an integrated hierarchical system. Classifications that focus on peatlands as ecosystems are largely observational, requiring in-depth field observation and documentation (Lindsay, 2016).

From the perspective of climate science, accounting for carbon stocks in peatlands is essential for the carbon inventory, carbon sequestration and conservation (Law et al., 2015; Xu et al., 2018). Minasny et al. (2019) present a review on digital mapping of peatlands with calculations for carbon stock accounting. They argue that the amount of carbon in peat depends on the peatland extent, peat thickness, carbon content and bulk density. There are numerous, and often complex, expensive and time-consuming, methods for determining peatland extent (Dargie et al., 2017; DeLancey et al., 2019; Lourenco et al., 2022), whereas peat thickness, carbon content and bulk density can be determined by relatively simple and well-established field and laboratory methods (Nelson and Sommers, 1996; Chambers et al., 2011; Parry et al., 2014; Minasny et al., 2019).

Table 3. Peat defined according to depth from various sources.

Authors/country authority/organisation	Year	Country of study	Depth (m)
2nd International congress of soil science cited by Tie (1982)	1930	International	>0.5
FAO UNESCO	1974	International	>0.4. >0.6 if the organic material consists of sphagnum or moss or has a bulk density of less than 0.1
US science and education administration	1975	USA	>0.4
Soil Survey of Ireland cited by Cruickshank and Tomlinson (1990)	1990	Ireland	0.3
Soil Survey of England and Wales cited by Cruickshank and Tomlinson (1990)	1990	England and Wales	0.4
Soil Survey of Scotland cited by Burton (1996)	1996	Scotland	0.5
Canadian Agricultural Services Coordinating Committee	1998	Canada	0.1
FAO	1998	International	≥0.1
Baillie	2001	USA	>0.4
Joosten and Clarke	2002	International	>0.3
US soil taxonomy staff	2014	USA	>0.4
Osaki et al	2016	Indonesia	≥0.5
Russian Federation cited in Tanneberger et al. (2017)	2017	Russia	Peat ≥0.3, shallow peatlands <0.3
Netherlands cited in Tanneberger et al. (2017)	2017	Netherlands	>0.4
Romania cited in Tanneberger et al. (2017)	2017	Romania	>0.2
Panagos et al. (Joint Research Centre)	2020	European Union	>0.1 from the soil surface to a bedrock contact, or >0.4 from the soil surface

Peat definitions according to depth

Contradictions in peat definitions frequently apply to the minimum depth of the soil surface organic layer (Tanneberger et al., 2017; Xu et al., 2018; IPS, 2021). Peatlands have been defined as having a minimum thickness from 0.1-1 m (Bord na Móna, 1984; Joosten and Clarke, 2002; Montanarella et al., 2006; Xu et al., 2018). In many countries, peat depth is a key criterion which defines the area as a peatland (Xu et al., 2018; Page et al., 2011; Rieley and Page, 2016). The peat depth also affects the potential time period and total amount of GHG emissions the deposit will release if the peat is exposed to air or drained (Wüst et al., 2003). Peat depth is therefore a very important criterion for conservation purposes, affecting biodiversity and GHG emissions (Wüst et al., 2003; FAO, 2020). Literature, country authorities and scientific groups specify a minimum depth to be defined as a peat (Table 3), and if the purpose of defining the peat differs amongst these groups, a discrepancy in definitions is likely to occur (FAO, 2020). To confound matters, not all definitions of peat contain a threshold for minimum depth.

Sixteen peat and peatland definitions from various sources, spanning at least 11 different countries are listed in Table 3. The average depth among these sources is >0.3 m for a deposit to be defined as peat, but it ranges between >0.1 m and >0.6 m, with the most common depth threshold being >0.4 m. In more recent literature, peatlands as thin as 0.15 m have been

Table 4. Threshold proportion of organic carbon, organic matter and ash content that soils must contain to be considered peat.

Authors/country authority/ organisation	Year	Country of study	Organic carbon (%), by weight	Organic matter (%), by weight	Ash content (%), by weight
Arman	1923	USA	—	20–100	<80
2nd International congress of soil science cited by Tie (1982)	1930	International	—		<35
Davis	1946	USA	—	65–100	<35
ASTM	1969	USA	—	>75	—
US Science and Education Administration	1975	USA	>12–18	—	
Kivinen et al	1979	International	—	50–100	0–50
Kearns et al	1982	USA	—	75–100	0–25
ASTM (Purnomo et al., 2012)	1982	USA	—	75–100	0–25
Mankinen and Gelfer	1982	USA	—	>50	<50
Andrejko et al	1983	USA	—	75–100	0–35
Landva et al	1983	USA	—	80–100	0–20
Jarret	1983	USA	—	75–100	0–25
Bord na Móna	1987	International	12–18	—	
Andriesse	1988	International	12–18	—	
Moris	1989	Malaysia	—	65–100	0–35
FAO UNESCO	1997	International	>12–18	—	
Canadian Agricultural Services	1998	Canada	>17	>30	—
FAO	1998	International	>12–18	>20–30	—
Baillie	2001	USA	>12–18	—	—
Joosten and Clarke	2002	International	—	>30	—
Wüst et al	2003	International	—	>45	0–55
Huat et al	2011	International	—	>65	—
Indonesian Ministry of agriculture (Purnomo et al.,2012)	2012	Indonesia	—	>65	—
Observation and Statistics Service (SOES, 2013)	2013	France	≥20	—	
US Soil Taxonomy Staff	2014	USA	>12–18	—	
Osaki et al	2016	Indonesia	>12	–	≤35%
Schulz et al	2019	Germany	—	>30	—
Panagos et al. (Joint Research Centre)	2020	European Union	>20	—	

recognised to hold a larger proportion of carbon stock compared to a high-carbon stock forest growing on mineral soil (Barthelmes et al., 2016). Most definitions do not recognise or classify thin peatlands; only the Russian Federation define both peat >0.3 m and paludified shallow peatlands <0.3 m (Tanneberger et al., 2017). Shallow peatlands are often more drained and degraded as they are not recognised in definitions (FAO, 2020). Thin peatlands should be included in national inventories, including the status of peatland health, reported emissions and monitoring to ensure peatland preservation (Van der Velde et al., 2021). Such monitoring systems would not be possible if inventories are based on older or even outdated definitions that do not recognise thin peatlands (FAO, 2020).

Peat definitions according to organic carbon, organic matter and ash content

The threshold proportion of organic carbon, organic matter and ash that soils must contain to be considered peat varies among countries and disciplines (Table 4). The majority of the definitions relate to thresholds of organic matter and not organic carbon. Total organic matter is different from total organic carbon as it includes all the elements that make up organic compounds, not just carbon (Nelson and Sommers, 1996). Of the 11 definitions used that stipulate a threshold for organic carbon percentage, nine use the same criteria as those presented in FAO: 12 and 18% depending on the proportion of clay in the soil (FAO 1998). This threshold is commonly used to describe histosols (Montanarella et al., 2006). The threshold is slightly different in France, which uses the value of ≥20% organic carbon (SOES, 2013) and for the Joint Research Centre based in Europe which stipulate that 12–20% organic carbon is organic-rich and >20% organic carbon is peat (Panagos et al. 2020).

According to the FAO (1998) definition, which has been used in the IPCC 2006 Guidelines for national greenhouse gas inventories and the IPCC 2013 Wetlands Supplement (IPCC, 2014), soils are organic if they satisfy requirements 1 and 2, or 1 and 3 from the following list:

1. 'Thickness of organic horizon greater than or equal to 10 cm. A horizon of less than 20 cm must have 12% or more organic carbon when mixed to a depth of 20 cm.
2. Soils that are never saturated with water for more than a few days must contain more than 20% organic carbon by weight (i.e. about 35% organic matter).
3. Soils are subject to water saturation episodes and have either:
   a. at least 12% organic carbon by weight (i.e. about 20% organic matter) if the soil has no clay; or
   b. at least 18% organic carbon by weight (i.e. about 30% organic matter) if the soil has 60% or more clay; or
   c. an intermediate proportional amount of organic carbon for intermediate amounts of clay'. (FAO, 1998: 45).

Organic soils are differentiated from mineral soils based on the dry weight percentage of organic carbon (FAO, 2020). In soil science, soils are considered organic when the threshold of 18% carbon is reached (FAO, 1998; Tubiello et al., 2016). According to Kazemian (2017), soil scientists define peat as organic soil with organic content of >35%, hence soils can be considered organic but not considered peat where the organic content is below this threshold. For example, in geotechnical engineering all soils with an organic content >20% are known as organic soil, while peat is an organic soil with organic content >75% (Kazemian, 2017). The FAO (2020) argues that this distinct value differentiating organic soil (18% carbon) is not suitable from the climate science perspective as the percent organic carbon does not include details regarding volumetric carbon content, the amount of carbon that would be emitted if the peatland were to dry and be exposed to oxygen.

If volumetric carbon content is considered, mineral soils and peatlands can emit the same amount of carbon dioxide (FAO, 2020). This is because by comparison, although mineral soils have much lower carbon content, the weight of mineral soils is much more than peat (organic soils) and therefore have just as much carbon (Nelson and Sommers, 1996). The FAO (2020) argues that the traditional definition of a peat soil based on 18% carbon content by weight or higher is thus problematic as many soils with lower carbon content – but equal or higher emission potential – can be overlooked by historical definitions. The problem of low-percentage and high-density carbon soils, which has already been recognised by various countries reporting emissions from peaty soils or peat-like soils, needs more attention from the scientific community (Barthelmes et al., 2018).

While the use of threshold values of organic carbon percentage presented in Table 4 are broadly similar, thresholds for organic matter and ash vary greatly among the definitions. The range of organic matter (Table 4) is 30–100%; the 20–100% from Arman (1923) defines organic soils and not peat.

The most common threshold is 75–100%, relating to definitions originating from the USA during the 1980s 65–100% organic carbon (proposed first during 1946, and repeated as recently as 2016) is also common among definitions originating from Malaysia, Indonesia, USA and international studies. Joosten and Clarke's (2002) and the FAO's (1998) definitions concur in terms of organic matter percentage with Joosten and Clarke (2002) requiring >30%, and FAO (1998) requiring 30% depending on the clay content. When considering the minimum percentage organic matter (by weight), the average from all (18) of the definitions presented in Table 4 which use organic matter as a defining criterion is 55%. This is almost double the threshold presented by Joosten and Clarke (2002) and FAO (1998).

Ash content by percentage weight also varies from 0–80% according to the definitions presented (Table 4). The most common value is 0–35% (proposed as early as 1930 and as recent as 2016) from definitions originating in Malaysia, Indonesia, USA and international studies. According to Wüst et al. (2003), peat classification systems based on ash content do not differentiate between biogenically derived and inorganic terrigenous or detrital matter. Consequently, peat samples with similar ash contents may contain very different amounts of detrital mineral matter and have different physical and chemical properties (Wüst et al., 2003). In more recent definitions since the start of the 21st century, the use of ash as a criterion became less frequent than those that were proposed during the 1970s and 1980s (Table 4).

Implications of disparate definitions

Global and regional estimates of peatland areas and their carbon stock vary widely (Minasny et al., 2019). Several inventories have been produced by compiling rough country estimates and soil maps from global (Maltby and Immirzi, 1993; Joosten, 2010; Yu et al., 2010; Xu et al., 2018) and tropical (Page et al., 2007, 2011; Rieley and Page, 2016) perspectives. Each of these inventories has different results in terms of area, carbon stock, carbon density, average peat thickness and assumed carbon content (Minasny et al., 2019). The large data ranges have been attributed to the compilation of different estimations from various sources (Joosten, 2010; Page et al., 2007, 2011), and the recycling of data without careful consideration of the level of accuracy and the inventory techniques used to arrive at those estimates (Joosten, 2010; Rieley and Page, 2016). As noted by Joosten (2010), acquiring a consistent global overview of peatlands is highly complex, caused by several factors including differences in typologies, scale of analyses, changes in extent over time and error calculations in units of measurement.

While a standardised inventory approach is required, it is challenging to determine whether one definition of peat should take precedence over another, even when considering the average or most common criteria used as a basis for each definition. The ranges in parameterisation are too broad. The use of specific defining criteria is also inconsistent, as some definitions focus on certain criterion and fail to acknowledge others. Only the FAO (1998) definition for peat according to minimum organic carbon content is consistent amongst most definitions that use organic carbon as a defining criterion. However, the 18% minimum organic carbon threshold has received criticism in recent literature (FAO, 2020), especially with regards to volumetric carbon (Barthelmes et al., 2016). The definitions from FAO (1998) and Joosten and Clarke (2002) are the most citied and therefore the most acceptable to use, however, the minimum thickness of 0.3 m from Joosten and Clarke (2002) has also been criticised as thin peatlands (<0.3 m) are overlooked (Barthelmes et al., 2016; FAO, 2020). What is unlikely, and probably impossible, is to create a definition that is applicable in all circumstances across all disciplines, unless the driving force behind the definition is that of peatland preservation. In accordance with the current trend in literature, the preservation of peatlands should take precedence, rather than determining whether the peatland deposit meets the defining criteria thresholds.

Recommendations and considerations for future peatland definitions

Through collaboration of academia and national institutions, the decisions made in the early definitions

regarding soil types and classifications, ecological and physical conditions for the identification of an area as a peatland, greatly influence a country's peatland mapping methodologies, future conservation strategies and GHG emissions (FAO, 2020). Due to historical reasons, conservative approaches in defining peatlands have been used (Intergovernmental Panel on Climate Change IPCC, 2014). As a recommendation from the IPCC working groups, a conservative approach for the definitions of peatland should use a minimum thickness of 0.1 m, which would serve most monitoring and preservation objectives and recognise thin peatlands (Intergovernmental Panel on Climate Change IPCC, 2014; FAO, 2020). Regarding organic carbon, the FAO (2020) recommend that the boundary between organic and mineral soils could be better drawn at 5% carbon owing to volumetric carbon content.

In accordance with the recommendations from the IPCC working groups and FAO (IPCC, 2014; FAO, 2020), we propose that a peatland be defined as an area containing peat soil having at least 5% organic carbon through a depth of at least 0.1 m. At the time of identification, the peatland can be with or without vegetation and be either waterlogged or not waterlogged. The motivation behind this definition is for conservation purposes and from the perspective of climate science, preservation and carbon accounting. Following peatland identification, it is critical to state four important physical and chemical characteristics (irrespective of scale) of the peatland deposit and peat soil: 1. Peatland extent, 2. peat thickness, 3. peat carbon content and 4. peat bulk density measurement (volumetric carbon content). Volumetric peat carbon data should be included as part of peatland assessments and inventories, especially data from low-percentage and high-density carbon soils to address the shortfall in literature pertaining to 'peaty soils' and 'peat-like soils' (Barthelmes et al., 2018). Estimation of carbon storage and potential GHG emissions is required, and the status of the peatland should be determined and thereafter the deposit should be monitored and protected.

In FAO (2020) the authors highlight that in order for peatland preservation to occur, the focus of national authorities must be placed on mapping peatland extent with accuracy, and in this review, we extend this focus to include data regarding the carbon inventory and carbon emissions potential of each deposit. The implication is that peatland deposits should not just be inventoried as if they represent a reserve that is in a steady state, but emphasis should also be placed on the dynamic of whether a peatland deposit is actively growing (sequestering carbon) or being lost. The critical dimension in climate science is the flux rate, and actively growing peatlands need specific measures to be put in place to preserve them. Details regarding the range of peat carbon content, peat depth and peat bulk density should be included to address potential GHG emissions due to peatland degradation, and ideally the growth dynamics should become part of the routine peat inventory. In this way, it is less important whether the peatland meet the defining criteria, and more important that the deposit is mapped, documented, monitored and preserved.

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CHAPTER 5: ANGOLAN HIGHLANDS PEATLANDS: EXTENT, AGE AND GROWTH DYNAMICS

5.1 Brief synopsis

This study presents the first classification of the Angolan Highlands peatlands, including a map of the peat extent. In addition, analysis of the age and growth dynamics of these deposits are presented. This is a multi-disciplinary study that incorporates RS datasets, machine learning and GEE with AMS radiocarbon dates of peat cores. Tropical peatland deposits are poorly mapped and documented within the literature. This is an important contribution as the study provides a first conservative estimate of the extent of these peatlands, contains details of peatland characteristics with respect to topographical data and RS indices concerning vegetation and standing water and suggests possible dates for peatland growth initiation, peatland growth dynamics, potential carbon storage, and threats to this deposit.

Author contributions:

Contributor role	**Author contribution**
Conceptualisation	Lourenco M, Woodborne S, and Fitchett JM
Methodology	Lourenco M, Fitchett JM, and Woodborne S
Validation	Lourenco M
Formal analysis	Lourenco M, Fitchett JM, and Woodborne S
Investigation	Lourenco M
Resources	Lourenco M
Data curation	Lourenco M
Writing – the original draft preparation	Lourenco M
Writing – review and editing	Lourenco M, Fitchett JM, and Woodborne S
Visualisation	Lourenco M
Supervision	Fitchett JM and Woodborne S
Project leaders	Woodborne S and Fitchett JM

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Angolan highlands peatlands: Extent, age and growth dynamics

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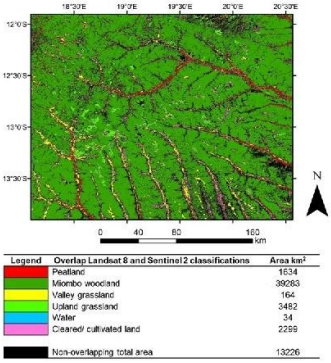
HIGHLIGHTS

- First peatland map in the Angolan Highlands using Google Earth Engine.
- The peatland extent in Angola is much larger than previously estimated.
- The peatlands have formed in lake environments, river floodplains and terraces.
- The African Humid Period could be linked is as a driver of peatland initiation.
- These previously unrecognised peatlands are under anthropogenic pressure.

GRAPHICAL ABSTRACT

The first map of the Angolan Highlands peatlands. An estimated peatland area of 1632 km^2 is derived from the overlap of the Landsat 8 and Sentinel 2 random forest classifications.



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ABSTRACT

The Angolan highlands are hydrologically and ecologically important, supporting peatland deposits. Peatlands are carbon rich ecosystems and are the largest terrestrial carbon store. We present a first estimate of the extent of peatlands in the Angolan Highlands, using Google Earth Engine. Our conservative estimate of peatland coverage is 1634 km^2, 2.65% of a mapped area spanning approximately 61,590 km^2. This is a crucial first step in providing the peatland carbon inventory for the region and to facilitate conservation and management strategies. We include the peatland characteristics with respect to topographic data and common remote sensing indices of Normalised Difference Vegetation Index and Normalised Difference Water Index. The results suggest that Angolan Highlands peatland is highly variable in terms of elevation, slope, vegetation cover and standing water occurrence. Radiocarbon dating of riparian peatlands suggest two stages of peatland initiation: one about 7100 cal. yr BP, during the African humid period, and another from about 1100 cal. yr BP to present after the African humid period ended. The temporal control of riparian peat formation is river dynamics and the formation of terraces. Source lake peatland is slightly younger and has average maximum age of 890 cal. yr BP. The Angolan Highlands ecosystem and peatlands are possibly under strain from anthropogenic influence and climate change, making this peatland deposit a potential carbon emission source.

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1. Introduction

Peatlands are of critical importance, having great economic, ecological, and cultural value (Ramsar, 2002; Limpens et al., 2008; Xu et al., 2018). Peatlands are terrestrial wetland ecosystems, providing a range of ecosystem services as they regulate and filter water flows (Frolking et al., 2011; Evers et al., 2017; DeLancey et al., 2019), aid in agricultural production (Page et al., 2011), are an energy source (Montanarella et al., 2006), and they support biodiversity (Minayeva et al., 2017; Xu et al., 2018). The most important peatland function, that is poorly quantified globally, is ecosystem carbon storage (Rieley and Page, 2016; Xu et al., 2018). Covering 3% of the earth's surface, peatlands are the largest natural terrestrial carbon store (Page et al., 2011), containing more carbon than all the world's forests (Joosten, 2011). Over the last decade, unprecedented growth of fossil fuel emissions and rising global temperatures have placed greater importance on carbon sinks (Friedlingstein et al., 2019; GCP, 2020; Loisel et al., 2021). Accurate mapping of peatlands is essential to determine the extent and carbon pool of peatlands in relation to global carbon stock, and to facilitate peatland preservation (Rieley and Page, 2016; Xu et al., 2018; Minasny et al., 2019).

Global estimates are often based on coarse country inventories and outdated global soil maps (Tanneberger et al., 2017; Xu et al., 2018; Minasny et al., 2019). Estimates of global peatland extent range from 1 to 4.6 million km^2, and carbon stock estimates range between 113 and 612 Pg carbon (Minasny et al., 2019). The large data ranges have been attributed to the compilation of different estimations from various sources (Joosten, 2010; Page et al., 2011), and the recycling of data without careful consideration to the level of accuracy and the inventory techniques used (Joosten, 2010; Rieley and Page, 2016). To confound matters, there is no globally accepted definition for peat or peatland (Xu et al., 2018; Minasny et al., 2019). Peat is classified as a soil with high organic matter content, which ranges from 30% to 100% depending on the definition used (Joosten and Clarke, 2002; Montanarella et al., 2006; Lindsay, 2010). Peatlands have been defined as having a minimum peat thickness ranging from 10 to 100 cm, subject to local classification schemes or scientific discipline (Bord na Móna, 1984; Joosten and Clarke, 2002; Montanarella et al., 2006; Xu et al., 2018). The high organic matter content results from a combination of peat forming vegetation and incomplete decomposition of organic matter due to waterlogged and anoxic conditions (Montanarella et al., 2006; Lawson et al., 2015).

Most known peatlands in the northern hemisphere have been mapped, covering parts of Europe and North America (Rieley and Page, 2016; Tanneberger et al., 2017). Deposits also occur in the tropics, mostly in Southeast Asia, the Caribbean and Central America, South America, and Africa (Rieley and Page, 2016). Tropical peatlands have been defined as peats that lie between the Tropics of Cancer and Capricorn, including both lowland and upland peat (Page et al., 2007, 2011). Africa reflects a diversity of peatland depositional environments that vary between sites and are mostly groundwater fed, reflecting the dry climate of the continent (Grundling and Grootjans, 2016). Large ombotrophic bogs do exist in wet equatorial regions such as Congo Basin (Davenport et al., 2020). Page et al. (2011) provide an estimate of peatland extent for Angola at 2640 km^2, a value that was later rereported in Rieley and Page (2016). The estimate was derived from the maximum area of 10,261 km^2 for histosol estimation in the Global Peatland Database (GPD, 2004), as histosols are regarded as peats in some global peat inventories (Montanarella et al., 2006; Xu et al., 2018). Joosten (2010) provides two estimates for Angolan peatland extent, one for 1990 and one for 2008, at 10,000 km^2 and 9910 km^2, respectively. Such estimates are not always strictly comparable due to different definitions of peat and sampling methods used (Rieley and Page, 2016).

Angola hosts unique habitats and species and is possibly one of the least documented biodiversity hotspot areas in the world (Myers et al., 2000). Exploratory surveys conducted by the National Geographic Okavango Wilderness Project (NGOWP) have identified extensive peat deposits in the eastern Angolan Highlands (Conradie et al., 2016; Goyder et al., 2018). The difficulty in accessibility and the large-scale mapping requirement of the Angolan Highlands means that the carbon inventory of this peatland deposit remains unknown. This study uses Google Earth Engine (GEE), a remote sensing (RS) approach, to map these peatlands. Through background knowledge of the Angolan Highlands, a land cover classification is provided, including a first map of the potential peatland extent. Peatland characteristics with respect to common RS indices such as Normalised Difference Vegetation Index (NDVI), Normalised Difference Water Index (NDWI) and topographic data – elevation and slope are included. Radiocarbon (^{14}C) dates of several peat cores collected from the study site also inform the possible control of peatland formation for the Angolan Highlands.

2. Methods

2.1. Study area

The Angolan Highlands is a central water source region for three major river basins of sub-Saharan Africa, contributing to the Congo basin to the north, the Zambezi basin to the east, and the Okavango basin to the south (Milzow et al., 2009; Abiodun et al., 2019). The highlands are the only source region of the Okavango Delta, an area rich in species diversity (Marazzi et al., 2017; Yurco et al., 2017). Civil war between 1975 and 2002, and widespread minefields have hindered access to the highlands (Conradie et al., 2016; Midgley and Engelbrecht, 2019) for nearly 50 years, and despite its hydrological and ecological significance, it remains little studied. The NGOWP has undertaken the most widespread scientific research in the highlands over the last decade. Since 2012, surveys have highlighted previously undocumented indigenous fauna (Conradie et al., 2016; Taylor et al., 2018) and flora (Goyder et al., 2018).

The Angolan Highlands mapped area for this study is in the southeast of Angola (Fig. 1). The mapped area spanning a latitudinal range of 11°54′–13°54′ S and longitudinal range of 18°05′–20°34′ E covers approximately 61,590 km^2, and has an elevation range from 1119 m.asl in the southeast of Moxico province to 1676 m.asl near the Cuito Source Lake. It is part of an extensive interior plateau that covers 65% of the country (Huntley et al., 2019). It is characterised by a vast peneplain draining Kalahari sands, with slow flowing rivers that meander across a gently sloping plateau towards the southeast (Goyder et al., 2018; Huntley et al., 2019). The region has cool annual temperatures of 15 °C and annual rainfall between 900 and 1320 mm, with less rainfall in the south (Abiodun et al., 2019; Huntley et al., 2019). The climate is strongly seasonal, with hot, wet summers from October to May and mild to cool, dry winters from June to September (Abiodun et al., 2019; Huntley et al., 2019).

The highlands lie within the Angolan miombo woodland ecoregion and contain tropical and subtropical grasslands, tree, and shrub savannas (Goyder et al., 2018; Huntley et al., 2019). The wide river valleys are characterised by extensive wet grasslands, peatlands, and ox-box lakes (Conradie et al., 2016). The impeded drainage and high precipitation in the rainy season cause temporarily waterlogged soils in the valleys that support humid grassland borders with humic topsoil and dwarf shrubs and prevent the development of miombo woodland (Conradie et al., 2016). The surrounding hills are dominated by miombo woodland (Conradie et al., 2016; Goyder et al., 2018). Miombo is the Swahili word for oak-like *Brachystegia*, a genus of tree comprising many species (Huntley et al., 2019; WWF, 2021). The miombo woodlands contain over 8500 plant species, they provide habitat for wildlife including the largest populations of elephants in Africa, and support millions of people who are dependent on the woodlands for their livelihoods (WWF, 2021). The NGOWP has extracted seven peat cores from four areas in the Angolan Highlands. Four samples were collected along the Lungui Bungu River, and the remaining three samples were collected from the Cuito, Cuanavale and Cuando source lakes (Fig. 1).

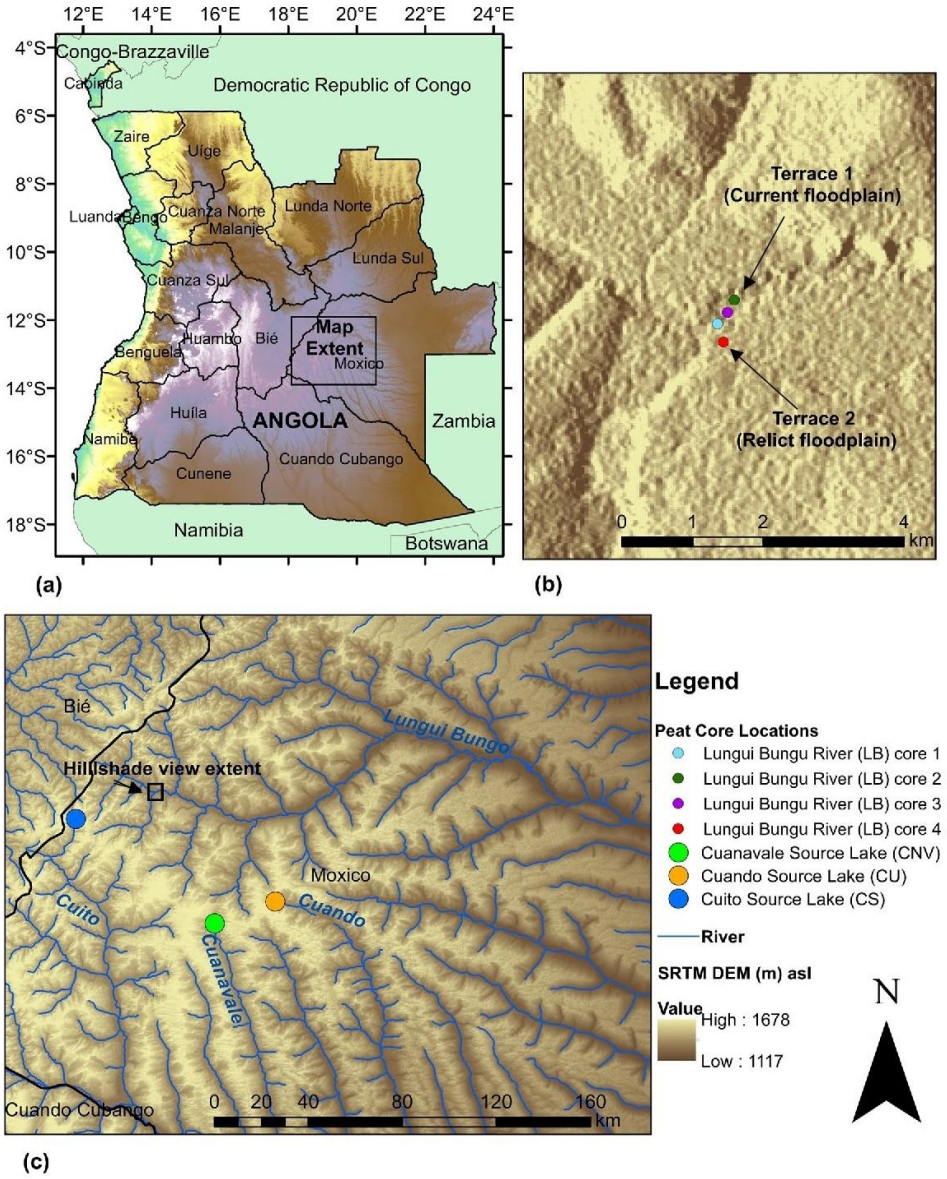


Fig. 1. Study site map, (a) Map extent within Angola, (b) Hillshade view of the four riparian Lungui Bungu River cores; samples 1, 2 and 3 lie within the current river floodplain, terrace 1, and sample 4 lies on the relict floodplain, terrace 2, and (c) Map extent for this study, showing the three remaining peat core locations and the hillshade view extent.

2.2. Peatland mapping

GEE has an extensive catalogue of RS datasets with various spectral and spatial resolutions that have been used for multiple applications, including land cover classifications and wetland mapping (Mahdianpari et al., 2019; Mutanga and Kumar, 2019; Amani et al., 2020). Due to the unique characteristics of peatlands, multisensory mapping approaches are often implemented, using optical, radar and LiDAR satellite imagery to identify and discriminate peatland from other wetland features (Mahdianpari et al., 2019; DeLancey et al., 2019). Satellite image selection is dependent on the characteristics of the peatland for each site (DeLancey et al., 2019; Amani et al., 2020). Although not exclusively, tropical peatlands have been mapped according to distinct features, including vegetation cover, standing water occurrence, and topography (Jaenicke et al., 2008; Draper et al., 2014; Dargie et al., 2017). GEE applications can operate independently, but due to the high geographic variability of peatlands, a level of ground truthing is required to support the GEE application (DeLancey et al., 2019; Mahdianpari et al., 2019).

2.2.1. GEE data exploration

All RS data was acquired, processed, and obtained directly from GEE (Supplementary Material: Table 1). There are no site-specific

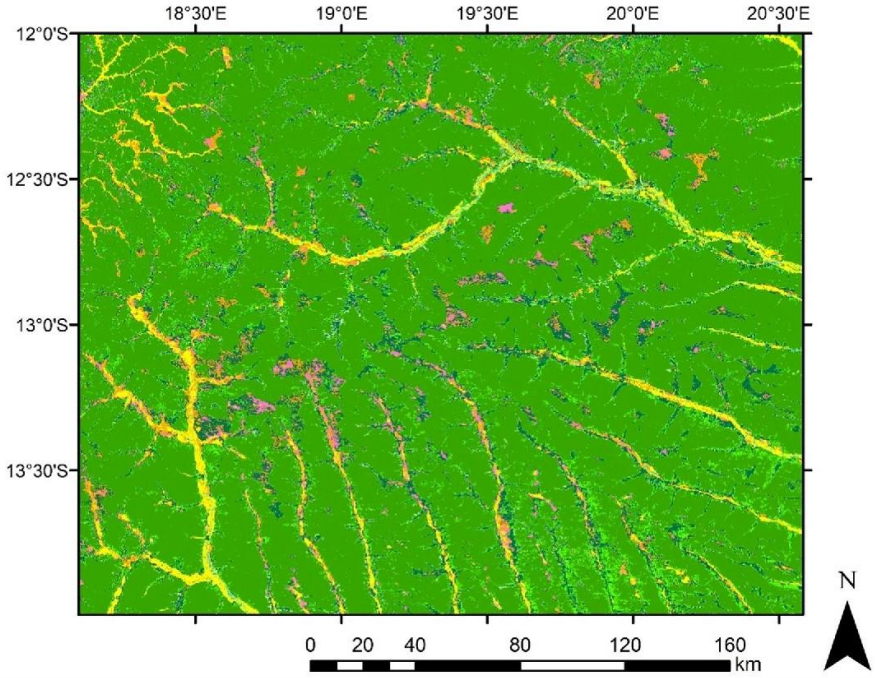
land cover maps of the area (Fig. 1c). Through exploratory analysis using GEE, the Copernicus Global Land Cover Layers: CGLS_LC100 collection 3 product was used to generate an unsupervised land cover classification (Fig. 2). The product classification has a 100 m resolution and a global accuracy of 80% (Buchhorn et al., 2020). It is used here to provide an overview of the land cover of the highlands. The product maps were produced over the period 2015–2019, spanning the dates of NGOWP field visits.

There are distinct land cover classes in the mapped area; most of the cover is *closed forest, deciduous broad leaf* which is classified in the hills surrounding the river valleys (Fig. 2). The river valleys are classified as *shrubs, herbaceous vegetation, herbaceous wetland* or *cultivated land*. According to the CGLS_LC100 product, the Highlands comprise 176 km^2 of *herbaceous wetland*, covering 0.29% of the mapped area. 72.70% coverage *is closed forest, deciduous broad leaf*, and 17.12% makes up the combined two *open forest* classes. This default land cover product has limited resolution and land cover classes do not relate specifically to peatlands; hence a supervised classification of the area was generated using GEE.

2.2.2. GEE classification data

USGS Landsat 8 (L8) and Copernicus Sentinel-2 (S2) satellite data were used to generate two separate land cover classifications of the mapped area. Although at different resolutions, these sensors have similar spectral bands and archives (USGS, 2021; ESA, 2021), that span the NGOWP expedition dates. The GEE catalogue stores the USGS L8 Surface Reflectance (SF) Tier 1 dataset and the Copernicus S2 MSI: Multispectral Instrument, Level-2A Surface Reflectance dataset, which are both atmospherically corrected products (USGS, 2021; ESA, 2021). Clouds from both datasets were removed from the image composites by filtering out images with greater than 5% cloud cover.

A random forest (RF) classification was performed on a cloud-free median composite of both the L8 and S2 datasets over the date range 2017-03-28 to 2021-02-14. The starting date corresponds to the S2 product availability on GEE. The L8 RF classification was based on six spectral bands at 30 m resolution, and the S2 RF classification was based on ten spectral bands at 20 m resolution (Supplementary Material: Table 1). RF is a non-parametric classifier and has been shown to outperform other advanced



Legend	Copernicus Global Land Cover Layers 100m	Coverage (%)	Area (km^2)
	Shrubs	3.84	2367
	Herbaceous vegetation	3.59	2208
	Cultivated and managed vegetation / agriculture	1.34	825
	Urban / built up	<0.01	<1
	Permanent water bodies	0.01	4
	Herbaceous wetland	0.29	176
	Closed forest, evergreen broad leaf	<0.01	<1
	Closed forest, deciduous broad leaf	72.70	44774
	Closed forest, not matching any of the other definitions	1.12	692
	Open forest, deciduous broad leaf	6.85	4221
	Open forest, not matching any of the other definitions	10.27	6323
	Total	100	61590

Fig. 2. Copernicus Land cover class area and coverage of the Angolan Highlands.

machine learning tools such as Decision Tree (Thanh Noi and Kappas, 2018), is simpler to complete than Support Vector Machine (SVM), as SVM requires modification of many parameters (Rodriguez-Galiano et al., 2012), and is not sensitive to noise and overtraining (Gislason et al., 2006). RF can manipulate high-dimensional RS data and has shown high classification accuracies in various wetland studies (Mahdianpari et al., 2017, 2019; Whyte et al., 2018).

Six land cover classes were chosen for the classification. These include peatland, miombo woodland, valley grassland, upland grassland, water, and cleared/cultivated land. Identical training and testing polygons were used for both classifications, these object-based polygons were derived from the lower resolution RGB – 30 m optical L8 cloud-free median composite. A total of 75 polygons covering 5.69 km^2 were drawn on the GEE interface (Supplementary Material: Table 2 and Fig. 1). Polygons were drawn in the centre of distinct features that represented the land cover sites directly observed in the field, this was to reduce edge effect inaccuracies due to the difference in resolution between the two satellites. An object-based classification approach has been shown to be superior to a pixel-based classification for wetland mapping (Mahdianpari et al., 2019). The polygon data were randomly split, 70% used for training and 30% used for testing the classification, the error matrices for each classification were generated on the GEE console.

2.2.3. Validation and accuracy assessment of classifications

For validation purposes overall accuracy, kappa coefficient, producer accuracy, and user accuracy were calculated for each classification using the error matrices (Onojeghuo et al., 2018; Mahdianpari et al., 2019). The McNemar test (McNemar, 1947) was used to determine whether the accuracies of the individual classifications are statistically significant from one another. This non-parametric test is based on the classification confusion matrix which is based on a chi-squared (χ^2) distribution with one degree of freedom and assumes the number of correctly and incorrectly pixels identified pixels are equal for both classification scenarios (Onojeghuo et al., 2018; Mahdianpari et al., 2019). The equation for McNemar's test is:

$$\chi^2 = \frac{(f12 - f21)^2}{f12 + f21} \quad (1)$$

where $f12$ and $f21$ represent the number of pixels that were correctly identified by one classifier as compared to the number of pixels that the other method incorrectly identified, respectively. All statistical analyses were performed using Python 3.8.

2.2.4. Overlap calculation of the two RF classifications

The two independent RF classifications were exported from GEE to ArcMap 10.2 for visualization and layer calculations. The classifications were overlapped on top of one another using the Raster Calculator tool from the spatial analyst toolbox in ArcMap 10.2. An overlap and non-overlap map was generated, including an error matrix of overlap and nonoverlap area between the two RF classifications.

2.2.5. GEE vegetation and water occurrence data

Selected bands from the median L8 and S2 composites that were used in the RF classification were used to generate a NDVI a NDWI composite for each satellite. NDVI is one of the most widely used vegetation indices, describing the greenness, relative density, and health of vegetation (USGS, 2020). NDVI values range from +1.0 to −1.0. Negative values indicate water bodies, while low NDVI values (0.1 or less) indicate barren rock or sand. Sparse vegetation such as shrubs and grasslands may result in moderate NDVI values between 0.2 and 0.5 and high NDVI values between 0.6 and 0.9 correspond to dense vegetation such as forests (USGS, 2020). The equation for NDVI that was used is (Rouse et al., 1974):

$$NDVI = \frac{(Near\ Infrared\ Band - Red\ Band)}{(Near\ Infrared\ Band + Red\ band)} \quad (2)$$

NDWI refers to at least two separate RS derived indices related to liquid water: one defined by McFeeters (1996), is used to monitor changes to water content in water bodies, using the green and Near Infrared (NIR) bands. Another is defined by Gao (1996), which uses the NIR and Shortwave Infrared (SWIR) bands to monitor changes in water content of leaves. This study uses the index as defined by McFeeters (1996), as tropical peatland features have been mapped according to standing water occurrence (Draper et al., 2014; Dargie et al., 2017). NDWI values range from +1.0 to −1.0, the NDWI of Mcfeeters (1996) was used to maximise the typical reflectance of water features, which have positive values, while soil and terrestrial vegetation have zero or negative values (Mcfeeters, 1996). The equation for NDWI that was used is (Mcfeeters, 1996):

$$NDWI = \frac{(Green\ Band - NIR\ Band)}{(Green\ Band + NIR\ band)} \quad (3)$$

2.2.6. GEE topographic data

The 30 m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) provided by NASA was used to provide three topographic map layers: elevation, slope and hillshade. Slope represents the angle of the terrain in degrees and hillshade is a 3D representation of the surface, with the sun's relative position used for shading the image (ESRI, 2016). Hillshade is used for illustrative purposes.

2.2.7. Peatland characteristics with reference to NDVI, NDWI and topographical data

The individual L8 and S2 peatland classes from each RF classification were joined to the respective vegetation (NDVI) and standing water occurrence (NDWI) datasets from each respective satellite. The L8 peatland class was joined to the two topographical raster datasets (elevation and slope) as it has the same resolution of 30 m. When joined, distribution plots from the joined data were produced to demonstrate the peatland characteristics with reference to NDVI, NDWI and topographical data.

2.3. Peat core dating methods

2.3.1. Peat core collection and subsampling

Two peat cores were extracted from each sampling site. The cores were collected in two separate NGOWP expeditions, the first made use of a Russian corer to collect the source lake cores. A Russian corer cuts the core in a horizontal plane, which reduces any mixing of material which occurs during vertical cutting of the core (De Vleeschouwer et al., 2010). The second expedition collected cores in the riparian zone of the Lungui Bungu River by pressing c.120 mm diameter stainless steel tubes vertically into the deposit, thereafter the peat surrounding the core was excavated. In all cases, the peat cores terminated when the equipment entered white sand. For this study, the lowermost section of the peat core is deemed the basal age of the individual core. The source lake cores were refrigerated <4 °C and were subsequently subsampled at 2 cm resolution in the laboratory; in-field subsampling could not be performed in the remote source lake areas. The LB cores were subsampled at 2 cm (LB core 1) and 1 cm (LB cores 2–4) resolution in the field. Cores were removed from the stainless-steel sampling tube and split in half. The outer surfaces were cleaned to minimize any impact of the coring technique. Thereafter each aliquot was carefully sliced from the cleaned core and subsampled for dating analysis.

2.3.2. AMS dating strategy and dating technique

The AMS sampling strategy focused on core top, core base, and one intermediate sample for the CU and each LB core. A high-resolution strategy was implemented for the CS and CNV cores to better resolve additional core data, not reported here. Radiocarbon dating followed standard pretreatment using acid (HCl), alkali (NaOH), and acid (HCl) followed by extensive washing with deionized water (Brock et al., 2010). Plant rootlets were removed using tweezers. Samples were oven dried and aliquots of the ultra-fine organic component were combusted in evacuated glass

tubes with CuO and Ag (Brock et al., 2010). The resulting CO_2 was graphitized before measuring the ^{14}C content. Radiocarbon dates were calibrated using the Southern Hemisphere SHCal20 model (Hogg et al., 2020). Radiocarbon dating was performed at iThemba Labs, Wits, South Africa. Age-depth models were calculated using the Bayesian BACON approach to age-depth modelling (Blaauw and Christen, 2011).

3. Results

3.1. Random Forest classifications

The individual RF classification maps show distinct separation of all land cover types at the respective resolutions (Fig. 3). Peatlands are generally classified in the river valleys alongside valley grassland and water. The miombo woodland dominates the landscape, upland grasslands are classified as distinct features within the miombo woodland and cleared/cultivated land are classified in areas surrounding the river tributaries and main water courses.

3.2. Accuracy assessment

The accuracy assessment reveals a high overall accuracy of 98.67% and 97.71% for the L8 and S2 RF classifications, respectively (Supplementary Material: Tables 3 and 4). The kappa coefficient values of 0.9836 (L8) and 0.9842 (S2) demonstrate a high level of agreement for each classification. Peatland had a user and producer accuracy >97% for both classifications. The McNemar test revealed that the difference between the accuracies of the L8 and S2 classifications was not statistically significant ($p = 0.9791$, McNemar's test chi-square value = 0.000687). While the accuracies of each classification are not statistically significant from one another, there are spatial and area discrepancies between land cover classes from each classification.

3.3. Spatial and area coverage overlap between the two classifications

An overlap and nonoverlap map of the two classifications was generated (Fig. 4). Overlap classes lie in distinct areas, with 48,363 km^2 (78.53%) of overlap and 13,266 km^2 (21.47%) of non-overlap between the two classifications. The majority of nonoverlap occurs in the river tributaries and in the North-east and South-eastern sections of the mapped area. The individual classifications have different resolutions; the edge effect caused by the different resolutions where most of the non-overlapping is shown on the edges of distinct land cover features (Fig. 4b). The overlap of the peatland class along the Lingui Bungu River is demonstrated (Fig. 4c). Peatland occurs on the modern river floodplain, terrace 1 – adjacent to the modern river, and on the relict floodplain, terrace 2 – adjacent to miombo woodland, both grassland classes and cleared/cultivated land (Fig. 4c).

An area calculation matrix of overlap and nonoverlap between each class was calculated (Table 1), the bold values are areas of overlap between the two RF classifications.

3.4. Peatland extent in the context of Angolan peatland

Three separate peatland estimates – one for each RF classification, and one for the overlap from both RF classifications are provided (Table 1). The overlap map area is reported here as the most conservative estimate of peatland coverage (1634 km^2). The mapped area covers just 4.94%, 61,590 km^2 of the total land area of Angola – 1,246,700 km^2. Providing the context of this deposit within the country is difficult, as the Angolan peatland estimates originate from studies that considered multiple countries from global and tropical peatland perspectives (Supplementary Material: Table 3).

3.5. Peatland characteristics with reference to NDVI, NDWI and topographic data

From visual inspection, the Optical (RGB), NDVI and NDWI depict the same landscape features. The NASA SRTM topographic data illustrates that river valleys are characterised by low slope angles and low elevation in comparison to the surrounding hills, hillshade is used here for illustrative purposes (Fig. 5).

Distribution plots were generated to provide additional peatland characteristics (Fig. 6).

For L8 NDVI, the peatland class has a range of values from −0.04 to 0.68, an average of 0.47 and mode of 0.48. For S2 NDVI, the peatland class has a similarly shaped distribution plot to that of L8 peatland class, the range is from −0.63 to 0.80, an average of 0.51 and mode of 0.5. For L8 NDWI, the peatland class has a minimum value of −0.62, average of −0.43 and mode of −0.45 and a positive maximum value of 0.02. For S2 NDWI, the peatland class is similarly shaped to that of L8 peatland class and L8 NDWI. The S2 peatland class has a large NDWI range from −0.71 to 0.65 and has an average NDWI of −0.53 and peak of −0.5. For SRTM elevation, the L8 peatland class distribution reveals multiple, wide ranging peaks in comparison to the NDVI and NDWI data that had either one or two peaks, that are much thinner. The average elevation for the L8 peatland class is 1316 m.asl, and has three peaks at 1350 m.asl, 1275 m.asl and 1190 m.asl. For SRTM slope, L8 peatland class has multiple peaks between 0° and 5°, a maximum slope of 40°, and an average of 3.36°.

3.6. Radiocarbon chronology

Each of the Lungui Bungu River peat chronologies shows reasonable age-depth profiles, except for LB core 2 where there is no possible age depth profile due to inversions (Fig. 7e). The LB core 2 sample was collected near an abandoned intensive peat agriculture field, and turbation of this site is evident in Google Earth imagery spanning several years. It is possible that the age inversion is the result of past agricultural working of the peat, although this should be expected for the upper layers, not at depth where the inversion occurs. The age models for cores 1, 3 and 4 suggest that these peat deposits started to grow about 1200 years ago, 1600 years ago, and 7100 years ago respectively. They also indicate that all the cores (including core 2) are still actively growing.

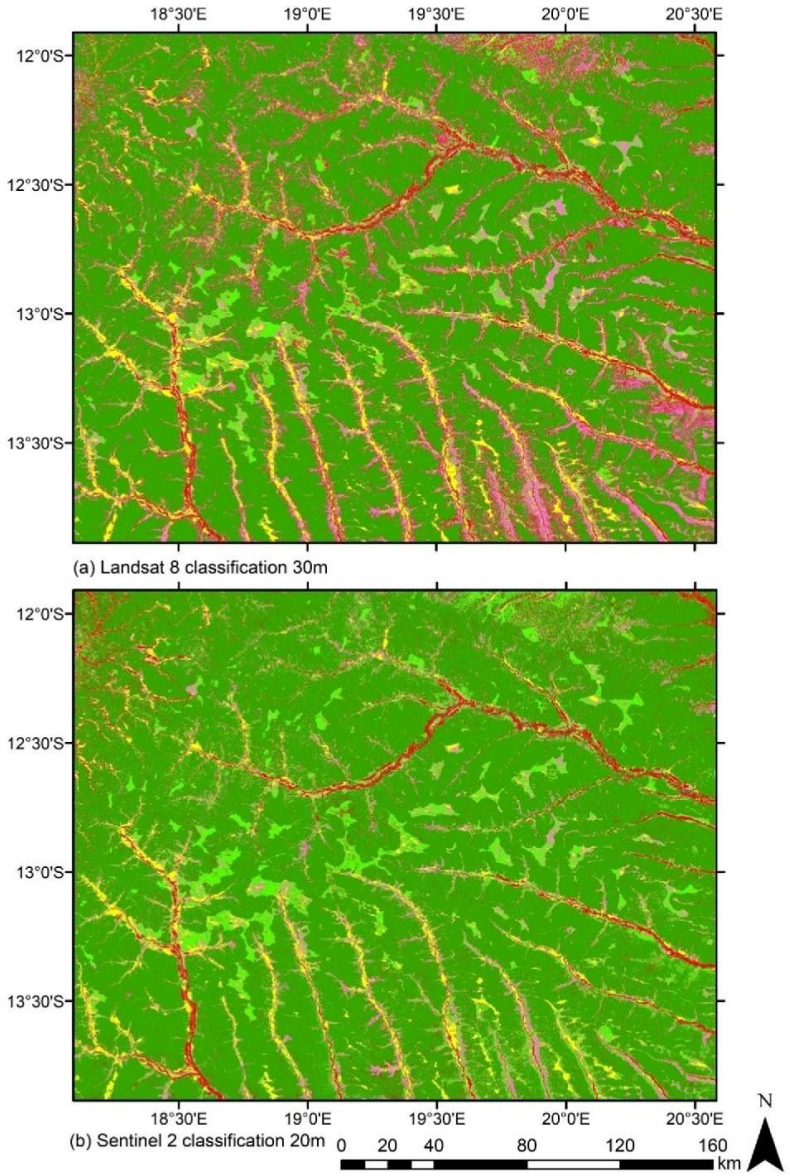
The age depth profile of the source lake cores suggests that the CNV core accumulated over the last 800 years, and the CU core accumulated over the last 1000 years. The pattern in the calibrated dates for the CS core indicate very rapid accumulation of approximately half the core, with all material dated below 25 cm having the same age. Between 25 and 19 cm depth there is a substantial jump in the age. This may be a single contaminated date (reject the date for 19 cm) in which case the upper half of the peat may have accumulated at a more gradual pace after the initial rapid growth. Alternatively, the date at 19 cm may be correct (there is no reason to reject it) suggesting slow growth of the peat for 200 years after the initial rapid growth, followed by intermediate growth in the last 200 years. All lake deposits are still actively growing. See Supplementary Material Table 6 for extended AMS dating results.

4. Discussion

4.1. Peatland extent

This study is the first to estimate and map the extent of the peatlands in the Angolan Highlands. The extent of peatlands in Angola is much larger than previously quoted from global studies, which has implications for national carbon budgets. Rieley and Page (2016) is the only study that mentions significant peatland deposits in Angola (Goyder et al., 2018). Rieley and Page (2016) mention that according to Bord na Móna (1984) and Shier (1985), there are extensive deposits in the valley of the River Cuanza, South-east of Catate, about 50 km from Luanda. Luanda is a coastal city that is over 600 km from the Angolan Highlands, meaning that the deposits mapped here have been overlooked (Goyder et al., 2018).

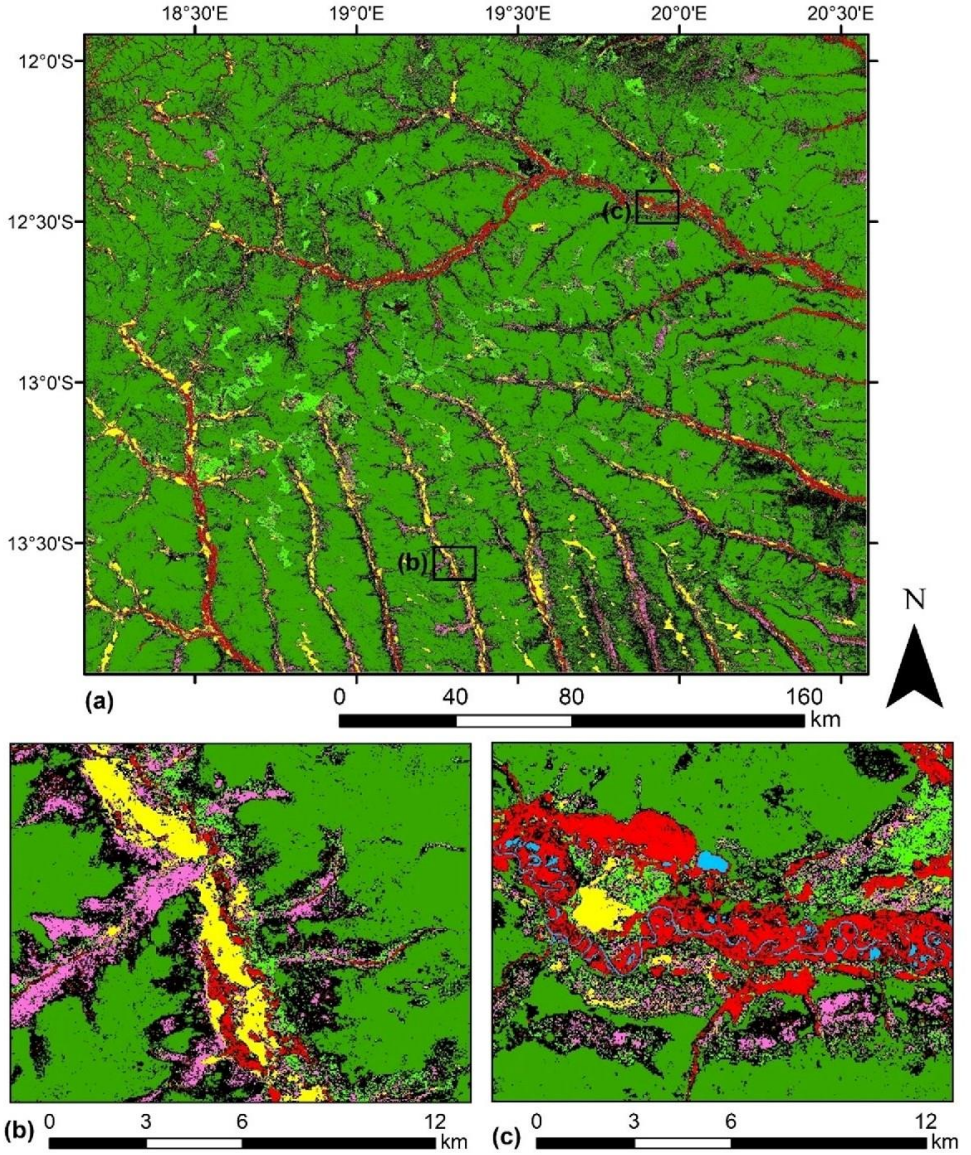
The estimate of 2640 km^2 from Page et al. (2011) was derived from the maximum estimate of histosols (10,261 km^2) minus the shallow histosols and organic soils (7621 km^2) from the GPD (2004). The maximum for histosols from GPD (2004) is similar to the estimates of Joosten (2010)



Legend	Class	Landsat 8 classification		Sentinel 2 classification	
		Coverage (%)	Area (km²)	Coverage (%)	Area (km²)
	Peatland	8.78	5408	5.99	3691
	Miombo woodland	66.02	40662	72.56	44689
	Valley grassland	3.57	2197	3.17	1952
	Upland grassland	8.39	5168	12.05	7421
	Water	0.10	60	0.10	61
	Cleared/cultivated land	13.14	8095	6.13	3776
	Total	**100**	**61590**	**100**	**61590**

Fig. 3. (a) Landsat 8 and (b) Sentinel 2 RF classifications including coverage and area of each class.

for 1990–10,000km^2 and 2008–9910km^2 where the 2008 estimate had a 0.90% reduction in area following expected peatland degradation over time (Joosten, 2010). These country estimates do not contain specific reference maps or location details that may be used to link them to the Angolan Highlands. Similarly, this estimate is specifically for the Angolan Highlands and cannot be extrapolated over the entire country. With no clear mention of the Angolan Highlands, it is likely that the estimate from this study is an addition to the best estimate (2640 km^2) reported by Page et al. (2011),



Legend	Overlap Landsat 8 and Sentinel 2 classifications	Area km²
	Peatland	1634
	Miombo woodland	39283
	Valley grassland	164
	Upland grassland	3482
	Water	34
	Cleared/ cultivated land	2299
	Non-overlapping total area	13226

Fig. 4. (a) Overlap and non-overlap map showing the extent of panel b and c, (b) and (c) are zoomed in sections of the mapped area.

Table 1
Land area coverage of overlap and nonoverlap between the two RF classifications.

Overlap area calculations (all values are in km^2)	S2 peatland	S2 miombo woodland	S2 valley grassland	S2 upland grassland	S2 water	S2 cleared/cultivated land	L8 class total	L8 class overlap (%)
L8 peatland	**1634**	2300	3	1181	21	268	5408	30.22
L8 miombo woodland	998	**39,283**	1	337	5	39	40,662	96.61
L8 valley grassland	3	3	**1631**	80	<1	479	2197	74.24
L8 upland grassland	427	543	26	**3482**	<1	691	5168	67.38
L8 water	23	2	<1	<1	**34**	<1	60	57.42
L8 cleared/cultivated land	606	2559	291	2340	<1	**2299**	8095	28.40
S2 class total	3691	44,689	1952	7421	61	3376		
S2 class overlap (%)	44.27	87.90	83.56	46.93	56.20	68.11		

meaning that the country estimate may be larger (>4274 km^2). The Highlands deposit would account for over half (61.90%) of the total peatland of Angola.

PEATMAP is one of the most recent estimates of global peatland extent: cataloguing 4,232,369 km^2 globally of which the African continent contributes 187,061 km^2 (Xu et al., 2018). This estimate is an addition to the

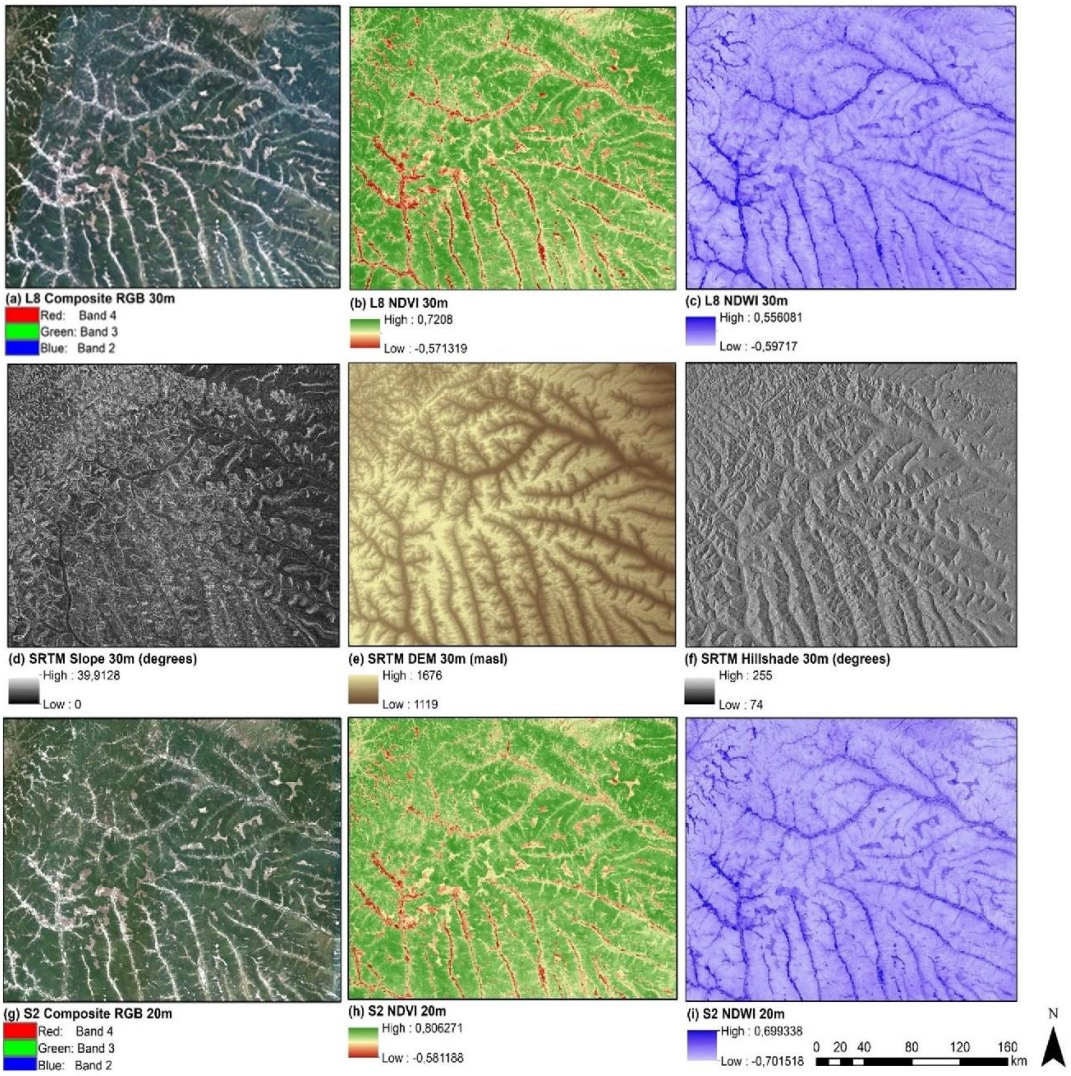


Fig. 5. Optical, vegetation, standing water occurrence and topographic data of the mapped area from Landsat 8 (a–c), NASA SRTM (d–f) and Sentinel-2 (g–i) sensors.

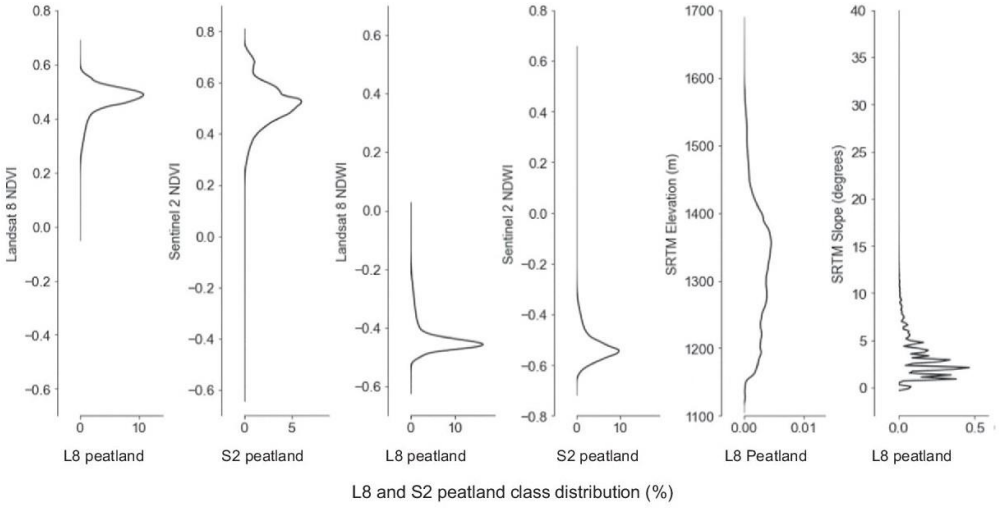


Fig. 6. Distribution plots for L8 and S2 peatland with respect to NDVI, NDWI and SRTM data (elevation and slope). The peaks of each distribution plot show the mode of values for individual peatland pixels. The NDVI and NDWI plots relate to each respective peatland class from each RF classification, the SRTM topographical data relates only to L8 peatland. See Supplementary Material Figs. 2–7 for distribution plots of all landcover classes.

African and tropical peatland extent. The headwaters of the Angolan Highlands contribute to the largest tropical peatland deposit to the north (Dargie et al., 2017); peatlands have also been identified to the south in the Okavango Delta (Grundling and Grootjans, 2016; Goyder et al., 2018); and there may be potential for further peatland mapping of the Zambezi basin to the east. Considering that the mapped area comprises only 4.94% of the country and approximately 16% of the Angolan highlands, it is likely that there may be more tropical peatland deposits to discover (Lawson et al., 2015), in the Angolan Highlands and surrounding basins.

This study provides a land cover classification of approximately 61,590 km^2 of the Angolan Highlands. The supervised L8 and S2 RF classifications demonstrate the benefit of field-based knowledge in comparison to a Copernicus global classification product, which returned 176 km^2 of *herbaceous wetland*. The critical landcover class 'peat' or 'peatland' is not available in this or any other product on GEE (GEE Data Catalogue, 2021). This is because peatland cannot be detected directly by RS on a global scale as the variety of peatland vegetation and depositional environments is too broad to assess peatland presence based only on surface landscape characteristics (Joosten, 2010; Xu et al., 2018; Minasny et al., 2019). As shown, regional mapping is achievable (Joosten, 2010), the kappa coefficient of each classification is >0.98, interpreted as having perfect agreement (Landis and Koch, 1977).

The overlap map area is reported as the most conservative estimate of peatland coverage (1634 km^2). This estimate is where peatland has been classified in both approaches. In each, the peatland class had over 97% producer and user accuracy. Reporting either S2 or L8 peatland coverage would likely overestimate the peatland coverage as only 30.22% of L8 peatland overlaps S2 peatland, and 44.27% of S2 peatland overlaps L8 peatland. The object-based training and testing polygons were identical for both RF classifications, and the differences between the accuracy of the classifications was not statistically significant ($p < 0.05$). It should be noted that these RF classifications are specific to the study site and are user driven.

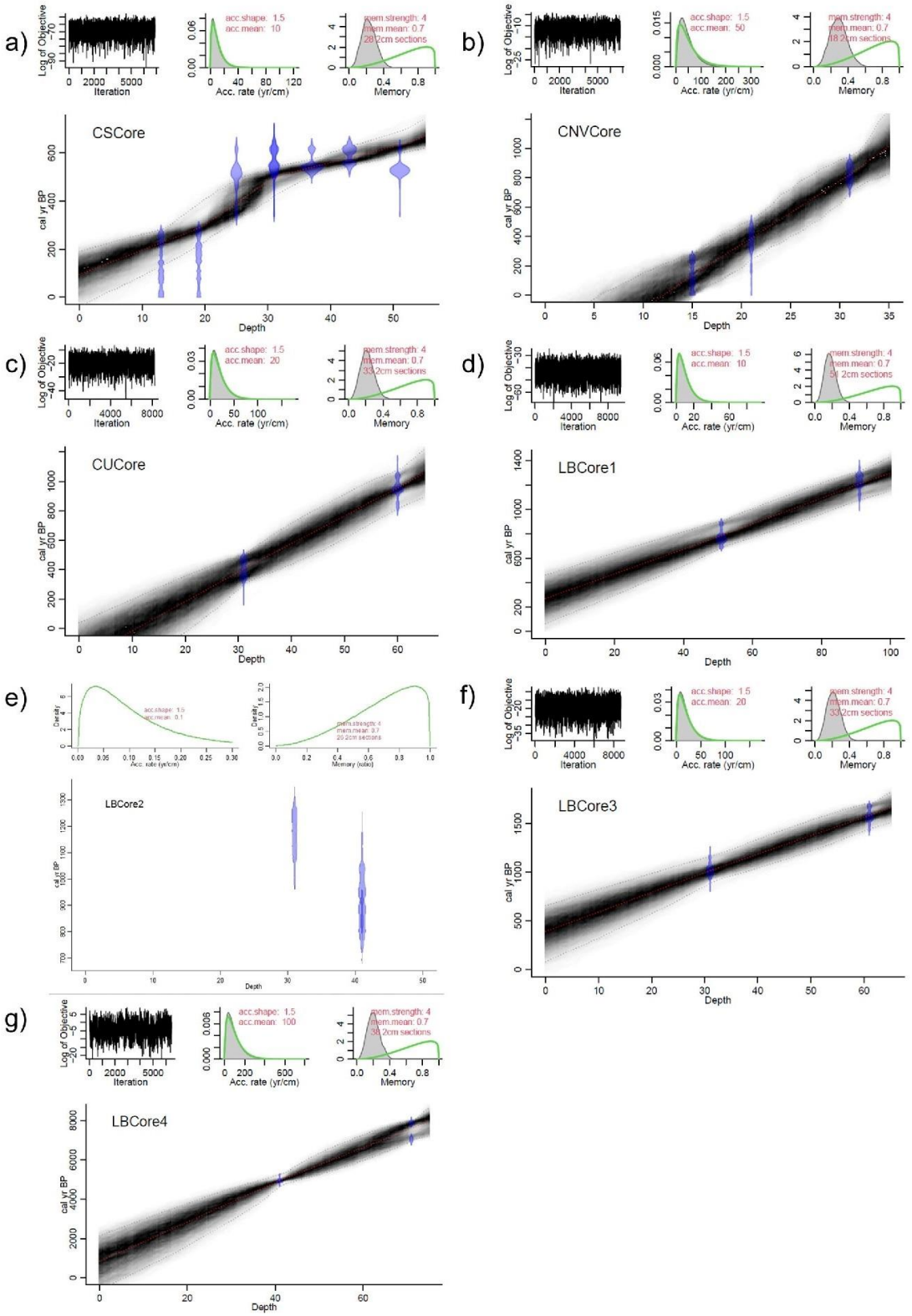
The differences between each RF classification can be explained by bootstrap aggregation – decision trees are sensitive to the data they are trained on, and small changes in the training set can result in significantly different tree structures (Gislason et al., 2006; Lee et al., 2020). RF takes advantage of this by allowing each individual tree to randomly sample from the dataset with replacement, resulting in different trees, known as bagging (Lee et al., 2020). With respect to feature randomness, RF only picks from a random subset of features, which forces more variation among the trees in the model and ultimately results in lower correlation across trees and more diversification (Gislason et al., 2006; Lee et al., 2020). The result is that with RF, trees are not only trained on different sets of data, but also use different features to make decisions (Gislason et al., 2006; Lee et al., 2020). Furthermore, the difference between the classifications can be explained by the number of bands – L8 used six spectral bands and S2 used ten spectral bands. The additional four Red Edge bands of S2 have been shown to produce better and comparable results to L8 and other S2 bands, respectively (Forkuor et al., 2018). The edge effect inaccuracies brought on by the difference in resolution between each classification is also responsible for some of the non-overlap between the two classifications.

The L8 and S2 classifications predict that peatland exists within the source lake and river valley environments, as was observed in field expeditions. With respect to the peatland class, most of the disagreement between the classifications occurs with the land cover classes of miombo woodland, upland grassland, and cleared/cultivated land. The disagreement between peatland and cleared/cultivated land can be expected as local communities target peatlands and riparian zones for cultivation, as observed at the LB core 2 location. Between the two classifications, peatland is often predicted in small, localised deposits within both the miombo woodland and upland grassland environments. These localised deposits of predicted peatland, away from the source lake and river environments, require further investigation in future field expeditions. In contrast, there is little disagreement with peatland and the valley grassland and water classes, these two classes both exist within the source lake and river valley environments.

4.2. Peatland in relation to NDVI, NDWI and topography

RS classification studies can be used either to identify peatland as a distinct land use (this study) or be used to identify vegetation communities and topographic features within a peatland environment (Lees et al.,

Fig. 7. Bacon Age-depth profiles for Angolan Highlands peat cores, panels a–c represent the age models for CNV: Cuanavale source lake peat, CS: Cuito source lake peat and CU: Cuando source lake cores, respectively. Panels d–g represent the age models for Lungui Bungu River cores 1 to 4, respectively.


a)
b)
c)
d)
e)
f)
g)
CSCore
CNVCore
CUCore
LBCore1
LBCore2
LBCore3
LBCore4
Depth
cal yr BP
Iteration
Log of Objective
Acc. rate (yr/cm)
Memory
acc.shape: 1.5
acc.mean: 10
mem.strength: 4
mem.mean: 0.7
28.2cm sections
acc.shape: 1.5
acc.mean: 50
18.2cm sections
acc.shape: 1.5
acc.mean: 20
33.2cm sections
acc.shape: 1.5
acc.mean: 10
36.2cm sections
acc.shape: 1.5
acc.mean: 20
33.2cm sections
acc.shape: 1.5
acc.mean: 100
38.2cm sections

2018; Oon et al., 2019). The NDVI, NDWI and topographical data were included to provide further details regarding this peatland deposit.

The NDVI for the peatland class had average of 0.47 and 0.51 for L8 and S2 classes respectively, with distinct peaks (modes) at 0.5, values typical of grassland and shrub vegetation (USGS, 2020). Comparable NDVI values for tropical peatlands are seldom reported. The NDVI of actively growing peatlands is specific to the region and season, reflecting the typical vegetation type growing on the deposit (Šimanauskienė et al., 2019). A total of 115 plant species were identified in the wetland habitat of the Cuito catchment alone (Goyder et al., 2018), 94 of which are associated with peat soils. This high variation of vegetation cover is reflected in the large range in NDVI associated with these peatland deposits. The NDVI values reported here are obtained from a cloud-free median RGB composite of both the L8 and S2 datasets over the date range 2017-03-28 to 2021-02-14, and therefore do not reflect the peatland growing season or growth under a changing climate. To ensure preservation of the Angolan Highlands peatland deposit, future investigation may focus on producing NDVI time-series, including seasonal variation in peatland vegetation coverage. NDVI is a good measure of photosynthetic activity and could be used to estimate peatland productivity (Wang et al., 2004; Boelman et al., 2003, 2005).

The NDWI for peatland had an average of −0.43 and −0.53, with distinct modes at −0.45 and −0.5 for L8 and S2 classes respectively, values indicative of terrestrial vegetation growth and not standing water (Mcfeeters, 1996). The NDWI for L8 peat has a maximum value of 0.02, whereas the S2 peat has a maximum value of 0.65 – which is typical of standing water (Mcfeeters, 1996). Although used as a predictor (Delancey et al., 2019), NDWI values for peatlands are rarely reported. The S2 RF classification is demonstrably more sensitive for both the vegetation (NDVI) and water (NDWI) indices over the L8 RF classification, shown by the larger range in each distribution plot. As with the NDVI data, similarly the NDWI plots do not reflect the peatland growing season through time. NDWI is a strong predictor of water table position (Kalacska et al., 2018), making it sensitive to peatland surface water depth (Zhang et al., 2014). Future investigation may focus on producing NDWI time-series, with particular emphasis on water table depth, hydrology, and precipitation.

The Angolan highlands peatland had a maximum elevation of 1676 m. asl, on average the peats are 1316 m.asl and the distribution plots had distinct peaks (modes) at 1350 m.asl, 1275 m.asl and 1190 m.asl. The shape of the density distribution curve of the L8 peatland class is most similar to the L8 valley grassland and cleared/cultivated land classes (Supplementary material: Fig. 6). These classes lie adjacent to one another within the river valleys, which suggest that the control on peat formation is strongly linked to geomorphology. Most of the peatland lies between elevations of 1150 m.asl and 1450 m.asl, and peat formation in upland valleys such as those in the Angolan Highlands also occur in Rwanda (2100 m.asl: Hategekimana and Twarabamenya, 2007), Lesotho (2400 m.asl: Trettin et al., 2008), and Burundi (1500 m.asl: Pajunen, 1996). In these high-altitude regions, the conditions for peat formation are similar to temperate regions (Andriesse, 1988; Page et al., 2011).

The slope distribution plots reveal that most of the peatland landscape is flat as most peaks occur between slope angles of 0–5°, with an average slope of 3.36°. Slope angles of up to 40° suggest that these peatlands are not limited to flat topographies, although this requires direct field measurement. Along the Lungui Bungu river, field observations of peat on steep slopes are associated with the incision of terrace 1 from terrace 2. Denoted by ^{14}C dates, before terrace 1 existed, the river was dominated by terrace 2, and the incision increased the local gradient (Fig. 8). In some cases, the incision is a cliff face which suggests that maximum slope values are most likely as a response to the local relief driven by the geomorphology of the area.

4.3. Onset of peat formation, potential carbon storage and peatland threats

The highland peatlands are diverse in that they are forming in lacustrine environments, on the current river floodplain and on relict river terraces. These peatlands are minerotrophic; with evidence from field observations and optical imagery, a distinct seep-line exists parallel to higher ground immediately adjacent to the peatlands. This seep-line is the inflow area of ground water, peatland only persists on terrace 2 where there are physical features that pond this water. These are low lying areas of terrace 2 and is why terrace 2 peatland is often patchy and associated with valley grassland and cleared/cultivated land. The valleys are a gentle V-shape, the peatlands all contour downwards towards the river. Effectively the peatlands are the upstream/downstream gradient of the river as they limit river flow. The headwater lakes are areas where steep hillside collapses block the river flow, and they form a lake with the same water supply as the river itself.

The maximum ages of the riparian Lungui Bungu River cores should not be seen as coincidental. The three cores from the current river floodplain, terrace 1, all have basal ages over 1100 years cal. BP while core 4 on terrace 2, has a distinctly different basal date of over 7100 years cal. BP. The age of 7100 years cal. BP may be linked with peat initiation and carbon accumulation related to the African humid period between ~11,000 and ~8000 years cal. BP (Schefuß et al., 2005; Shanahan et al., 2015). The dates are also comparable to those collected in the Central Congo Basin

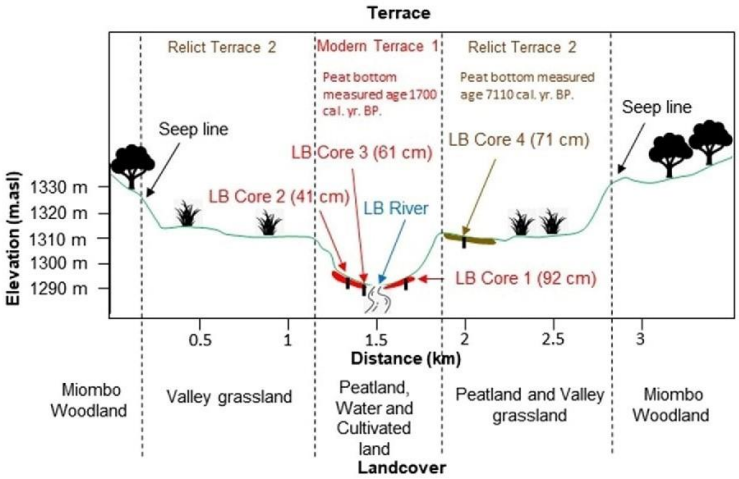


Fig. 8. Cross-section of the peat core sampling site at the Lingui Bungu River.

where the Cuvette Central swamp peats returned ages ranging from 10,554 to 7137 years cal. BP (Dargie et al., 2017). Ages of around 1100 years on terrace 1 indicate that the peat has continued to grow since the end of the African humid period at ~3000 years cal. BP (Schefuß et al., 2005; Shanahan et al., 2015) in the Lungui Bungu River.

Along the Lungui Bungu River sampling site, the peat formation on the modern riverbank (terrace 1) is almost ubiquitous, having a greater coverage than terrace 2, where only relict peat patches remain. Local farming practices target terrace 2 peat because it is easily drained. However, drainage also occurs on terrace 1, leading to oxidation and changes to the hydrological buffering that these peats offer. The terrace 1 peats are a control valve between ground water flow and the river, a highly important ecosystem service. Continued peat drainage also potentially destabilises the riverbank. The reduction in peat area on both terraces 1 and 2 may imply that the dynamics of peat in the Lungui Bungu River is a net source of atmospheric carbon rather than a sink on geological time. The age and dynamics of these terrace peats is therefore of considerable interest and warrant future investigation.

The ^{14}C dates reveal that the source lake cores are slightly younger (average basal age of 890 years cal. BP) than the riparian LB cores. The results from the CNV and CU cores suggest slow onset of peat growth that accelerates through time – acknowledging that the evidence for this in CU is based on only two dates. In contrast, the CS core shows extremely rapid peat growth initially, followed by a possible hiatus in growth. The rate of peat formation in the upper part of the CS core is consistent with the rapid rates seen in the CNV and CU cores. The mechanism that underlies the age profile for the CS core is not clear. It could be explained by a catastrophic erosion event, two pulses of growth, changes to climate or possible peat loss due to anthropogenic disturbance.

The average depth of the cores collected for this study is 63.6 cm, Goyder et al. (2018) – part of the NGOWP mention that they directly measured peat to a depth of at least 5 m at the Cuito Source Lake. AMS ^{14}C dating reveals that these peatlands continue to grow but have formed over the last few thousand years. The implications are that the deposit may store significant amounts of carbon (Goyder et al., 2018), and that these deposits have the potential to be an important part of the global carbon economy. This map is the first step in providing the carbon store and serves to promote preservation of the deposit. Future research specific to this study would require a complete ground field survey to verify the land cover classifications, with particular emphasis on peatland extent. In addition, to provide estimates of the carbon inventory, peat depth and bulk density are required.

The threats to the Angolan Highland peatlands and landscape can be linked to anthropogenic practices such as extensive fires, wood and peat fuel extraction, tree clearing, wetland drainage and overgrazing (Conradie et al., 2016; Taylor et al., 2018). Continued population growth, lack of financial means, subsistence agriculture and human pressure on the land are increasing in unprotected, rural areas of Angola (Catarino et al., 2020). These peatlands are highly susceptible to fire and slash and burn agriculture (Conradie et al., 2016; Taylor et al., 2018). The largest burnt areas in rural parts of Angola were recorded between 2003 and 2005, which is linked to the end of the civil war in 2002 (Catarino et al., 2020). During the war, there was emigration from rural communities to urban areas and agricultural fields were abandoned, and when the war ended some displaced people returned and started clearing land for agriculture (Catarino et al., 2020). In contrast, some protected areas of Angola exhibited decreasing trends in burning during that same period (Catarino et al., 2020). The role of fires and peatland degradation is well documented in the extensive tropical peatlands of South-east Asia (Rieley and Page, 2016; Page et al., 2007, 2011), highlighting the need to protect this deposit from the same process.

Angola is particularly vulnerable to climate change, with Regional Climate Models (RCMs) predicting consistent results of an increase of up to 4.9 °C by 2100 and increasing frequency and intensity of droughts for the twenty-first century (Carvalho et al., 2017). The semiarid and subhumid areas will be affected by a shift towards a drier regime (Carvalho et al., 2017), affecting peatland functioning and putting increased strain on rural communities that rely on peatlands for agriculture, water, and fuel (Grundling and Grootjans, 2016). Estimates in 2010 indicated that 10–15% of African peatlands are degraded, releasing 4.3% of global peat CO_2 (Joosten, 2010). These have likely increased. Future conditions associated with a combination of anthropogenic influence and climate change are expected to further increase carbon emissions owing to peatland degradation (Xu et al., 2018; Minasny et al., 2019).

5. Conclusion

The first land cover classification of the Angolan Highlands study area was produced using GEE. This classification includes a conservative area extent of peatland coverage, 1634 km^2. This is a crucial first step in providing the peatland carbon inventory and to facilitate conservation priorities and management strategies for the area and its surrounding basins, basins that are likely to contain additional unmapped peatland deposits. The relationship between peatland and vegetation cover, standing water occurrence and topographic data was included to further describe these peatlands. Radiocarbon dating of peatland cores informs the possible onset of peatland accumulation for the highlands and has uncovered additional questions about how they have formed and continue to grow. We emphasise that future research in this region is required to focus not only on peatland extent, but also investigate the peatland growth, vegetation, water, and carbon dynamics of this unique environment. Peatlands are extremely important ecosystems that globally, are under threat from anthropogenic influence and climate change, these peatlands are no different and have the potential to have net carbon emissions in future if they remain unprotected.

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CRediT authorship contribution statement

Mauro Lourenco: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Funding acquisition. **Jennifer M. Fitchett:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Stephan Woodborne:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.152315.

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CHAPTER 6: DROUGHT HISTORY AND VEGETATION RESPONSE IN THE ANGOLAN HIGHLANDS

6.1 Brief synopsis

In this study, an investigation of the drought dynamics for the Angolan Highlands are presented from the analysis of a 40-year CHIRPS precipitation and a 20-year MODIS vegetation growth record. The study reveals the contemporary seasonality of precipitation and vegetation growth for the region. It presents the 40-year drought history and the describes the relationship between drought and ENSO and regional synoptic systems. The implications of drought are discussed in this study, with specific reference to peatland vegetation growth under drought conditions and future climate scenarios. This is an important contribution as the study provides the first historical assessment of drought in the Angolan Highlands, a region which contains vulnerable rural populations that are dependent on rain-fed subsistence agriculture.

Author contributions:

Contributor role	**Author contribution**
Conceptualisation	Lourenco M, Fitchett JM and Woodborne S
Methodology	Lourenco M, Fitchett JM, and Woodborne S
Validation	Lourenco M
Formal analysis	Lourenco M
Investigation	Lourenco M
Resources	Lourenco M
Data curation	Lourenco M
Writing – the original draft preparation	Lourenco M
Writing – review and editing	Lourenco M, Fitchett JM, and Woodborne S
Visualisation	Lourenco M
Supervision	Fitchett JM and Woodborne S
Project leaders	Fitchett JM and Woodborne S

According to the above-mentioned CRediT system the author contribution was calculated as follows:

Lourenco M – 70%

Fitchett JM and Woodborne S – 30%

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ORIGINAL PAPER

Drought history and vegetation response in the Angolan Highlands

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Abstract
Drought negatively impacts health systems, agriculture, economies, energy, and the natural environment. The vulnerability of the Angolan Highlands rural communities that are dependent on rain-fed agriculture is a concern due to the prospect of climate change and the trajectory of increasing frequency of droughts in the region. The Angolan Highlands is an essential source water region for the Okavango Delta, and southern Africa more broadly. This study integrates Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and vegetation indices from moderate resolution imaging spectroradiometer (MODIS) in the first historical assessment of drought in the Angolan Highlands. Using the standardized precipitation index (SPI), eight distinct drought periods were identified: 1981–1982, 1989–1990, 1994, 1995–1997, 1999–2000, 2014–2016, 2017–2018, and 2018–2020, with the frequency of drought increasing since 1981. The relationship between drought occurrence and El Niño Southern Oscillation (ENSO) is not linear; with two of the eight drought periods occurred exclusively during El Niño years. The seasonality of precipitation, MODIS enhanced vegetation index (EVI), and normalized difference vegetation index (NDVI) are similar, with NDVI and EVI being lowest at the end of the dry winter months (August), and highest during the summer rainfall season. The strong relationship between precipitation and vegetation, anthropogenic pressure on the landscape, and increased drought occurrence are likely to lead to potential environmental degradation in future. Mitigation and adaptation strategies to drought may be required, especially concerning water resources and agricultural practices within the Angolan Highlands region.

1 Introduction

Drought is a persistent natural hazard and is one of the most damaging to health (Ebi and Bowen 2016), agriculture (Nath et al. 2017), economies (Ahmadalipour et al. 2019), and the natural environment (Bachmair et al. 2016). The World Health Organisation (WHO 2021) estimates that this phenomenon affects 55 million people globally each year, leading to famine, water shortages, migration, disease, and death (Ebi and Bowen 2016; Luetkemeier and Liehr 2019). Between 1900 and 2013, it is estimated that approximately 850,000 people died, and more than 350 million people were affected by drought events in Africa (Ahmadalipour et al. 2019; Luetkemeier and Liehr 2019). Across sub-Saharan Africa, major droughts occurred in the early 1970s, mid 1980s and early 1990s (Luetkemeier and Liehr 2019). Drought occurrence is intensifying in frequency and severity in southern Africa, presenting challenges to long-term water and food security in the region (Nhamo et al. 2019; Gore et al. 2020).

Angola experienced severe drought events in the early 1990s and 2000s (Rouault and Richard 2005) as well as a perennial drought from 2013 to 2016, and again in 2019 (Regional Vulnerability Assessment and Analysis Programme: RVAA 2019) which have been linked to the El Niño Southern Oscillation (ENSO; Luetkemeier and Liehr 2019; Gore et al. 2020). Angola also experienced drought during 2020/2021, when cumulative rainfall was 30% below the long-term average (Food and Agriculture Organisation of the United Nations: FAO 2021). The Angolan people are vulnerable during prolonged drought periods: A total of 11.1 million people (37%) of the population live in rural regions (RVAA 2019), and the majority of them practice rain-fed subsistence agriculture (Luetkemeier and Liehr 2019).

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Retrospective analysis of precipitation data is extremely valuable in determining the severity of past drought events, aiding in response development and mitigation strategies (Mishra and Singh 2010; Mlenga et al. 2019). The dependence of the Angolan population on hydroclimatic conditions underscores the importance of accurate assessment of past drought occurrence and drought monitoring for potential disaster management in future.

Traditional definitions consider drought to be an extreme precipitation deficit (González and Valdés 2006; AghaKouchak et al. 2021) in a specific region that persists for a defined period of time (Zargar et al. 2011). Physical drought types include meteorological, agricultural, and hydrological drought (Zargar et al. 2011). Additional drought types, which have received increased attention, include anthropogenic, socioeconomic, and ecological drought (Kchouk et al. 2022), with a new focus on drought being defined as a process and not a product (AghaKouchak et al. 2021). In addition to drought type, droughts are also characterized by severity, duration, spatial distribution, frequency, magnitude (cumulated deficit), predictability, rate of onset, and timing (Mishra and Singh 2010; Zargar et al. 2011). Determining drought onset, duration, and termination is complex, presenting difficulties in accurate and effective drought monitoring (Mishra and Singh 2010; Mlenga et al. 2019).

Over 100 different drought indices have been proposed, many of which are functions of precipitation with or without temperature, and with or without river discharge (Zargar et al. 2011). Common drought indices include the standardized precipitation index (SPI: McKee et al. 1993), percent of normal, Palmer drought severity index (PDSI: Palmer 1965), the standardized precipitation evaporation index (SPEI: Vicente-Serrano et al. 2010), Deciles (Gibbs and Maher 1967), crop moisture index (CMI: Palmer 1968), and reconnaissance drought index (RDI: Tsakiris and Vangelis 2005). The SPI is a widely used meteorological drought index that is simplified so that it only depends on precipitation data, resulting in a single numeric value (McKee et al. 1993; Komuscu 1999). In 2009, the World Meteorological Organisation (WMO) Lincoln Declaration recommended SPI as the primary meteorological drought index (Svoboda et al. 2012). This is because SPI allows the comparison between different climates and locations and can be used to monitor dry or wet periods for any location with regular precipitation data (McKee et al. 1993; Moreira et al. 2008). The index can be computed for multiple time periods, reflecting precipitation deficits of different water resources and can identify various drought types (Svoboda et al. 2012).

Reliance on meteorological data alone may be inadequate in monitoring drought across all regions, especially in southern Africa where data is likely to be incomplete, unreliable, unavailable, and untimely (Mlenga et al. 2019). In such situations, satellite imagery may be used to assess the spatial and temporal dimensions of drought. Satellite data can be used to obtain a better understanding of the pressures on water resources, vegetation, and society to drought (Didan 2015; Gao et al. 2020). The normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) are widely used drought indices obtained from satellite data (Didan 2015; Liou and Mulualem 2019; Gao et al. 2020). Both NDVI and EVI have been used for estimation of vegetation health, coverage, net primary production, crop growth conditions, yield assessments and estimation, vegetation type, phenology, and land cover changes, and contribute to drought monitoring and early warning systems (Brown et al. 2008; Liou and Mulualem 2019; Hua et al. 2019). Vegetation which is particularly vulnerable to drought can be studied for drought risk management and can be used to map areas affected by drought (Alamdarloo et al. 2018; Liou and Mulualem 2019).

The Angolan Highlands is the water source region for three major river catchments in sub-Saharan Africa, including the Congo River to the North, the Zambezi River to the East, and the Okavango system to the south (Lourenco et al. 2022). The Angolan Highlands support transboundary rivers that flow from Angola to Namibia, Botswana, Zambia, the Democratic Republic of the Congo, Mozambique, and Zimbabwe. The highlands are the only source region of the Okavango Delta, a UNESCO world heritage site (Marazzi et al. 2017; Yurco et al. 2017; UNESCO 2021). Civil war between 1975 and 2002 and persistent minefields have hampered access to the region, and despite its hydrological and ecological significance, it is little studied (Carvalho et al. 2017; Lourenco et al. 2022). Climate variability in the region is one of the strongest drivers of rainfall variability over a subcontinent that is largely dependent on rain-fed agriculture (Crétat et al. 2019; Huntley et al. 2019). Despite its importance, there are no studies, specific to this region that might explain the variability and history of drought, the potential vegetation response and consequences on local communities. This study integrates Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and the SPI with NDVI and EVI for historical assessment of drought monitoring in the southeast of the Angolan Highlands.

2 Methods

2.1 Study area

The Angolan Highlands study site is in the southeast of Angola, spanning a latitudinal range 11°54′-13°54′S and longitudinal range 18°05′-20°34′E, and covering approximately 61,590 km^2 (Fig. 1). It is part of an extensive interior plateau, characterized by a vast peneplain of Kalahari sand (Goyder et al. 2018; Huntley et al. 2019). The climate is

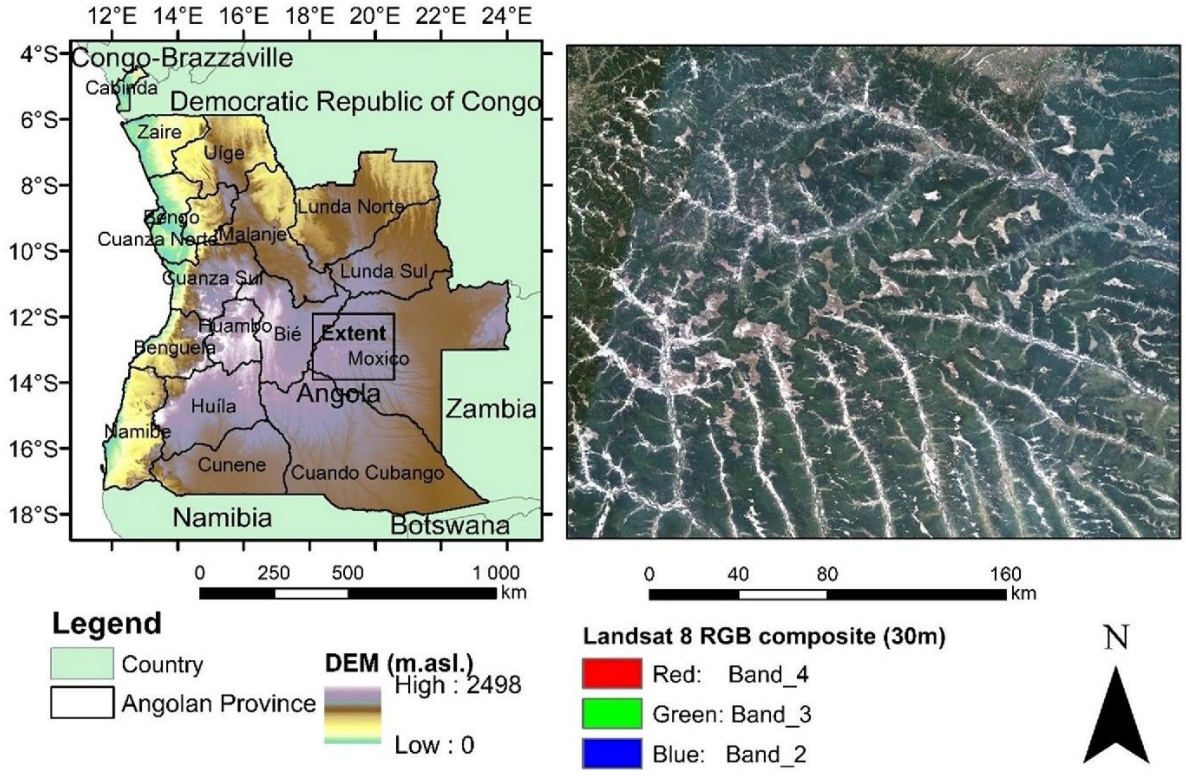

Fig. 1 Study area map showing the study site extent in Angola and a Landsat 8 (USGS, 2021) red, green blue (RGB) optical image of the study site

strongly seasonal, with hot, wet summers from October to May and mild to cool, dry winters from June to September (Abiodun et al. 2019; Huntley et al. 2019). The highlands lie within the Angolan miombo woodland ecoregion and contain tropical and subtropical grasslands, tree, and shrub savannas (Goyder et al. 2018; Huntley et al. 2019). The wide river valleys are characterized by extensive wet grasslands, peatlands, and ox-box lakes and the surrounding hills are dominated by miombo woodland (Conradie et al. 2016; Goyder et al. 2018; Lourenco et al. 2022).

2.2 Precipitation data

Studies of the climate of Angola have been hindered over the past four decades due to the collapse of the extensive network of weather stations during the civil war, and the resultant poor national coverage of meteorological data, and lack of reliability of climatic data collected (Huntley et al. 2019). The weather recording network reduced from 225 climatological stations in 1974 to zero in 2010, while the number of actively recording synoptic stations decreased from 29 in 1974 to 23 operational stations in 2010, of which 12 are automatic and 11 conventional (Huntley et al. 2019). Since 2010, the network has been strengthened by 22 automatic stations established by the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL, Huntley et al. 2019). A minimum of 30 years of continuous precipitation data are needed for reliable calculations of the SPI, and even longer archives are favourable (McKee et al. 1993). The precipitation data for the study has been collected from a remote sensing product, as historical climate data from weather stations, specific to this study area, are unavailable.

Historical precipitation data for the region were collated using the Google Earth Engine (GEE) platform. Precipitation data were obtained from the CHIRPS 30 + year quasi-global rainfall dataset (Funk et al. 2015). CHIRPS synthesises 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring (Funk et al. 2015). On GEE, daily precipitation data was collated for the period spanning 40 years from 1981–01-01 to 2020–12-31. The daily precipitation values represent the mean of all pixels over the delineated study area of interest at 5 km resolution. This data was used to create both a time-series of daily precipitation over the period

of interest, and to produce maps of the spatial distribution of precipitation over the region using ArcMap 10.2.

2.3 Standardized precipitation index

The SPI was calculated using the methods described by McKee et al. (1993). The SPI generator v.1.7.5 was used following the procedure specified in the WMO SPI User Guide (Svoboda et al. 2012). The SPI was calculated using the CHIRPS daily precipitation data which had no missing values over the full historic archive. The SPI calculation for any location is based on the long-term precipitation record for a period of interest. The SPI can be computed for multiple periods, but is commonly applied for 1-, 3-, 6-, 12-, 24-, 36-, and 48-month periods (Svoboda et al. 2012; Tirivarombo et al. 2018; Mlenga et al. 2019). Meteorological and soil moisture conditions (agriculture) respond to precipitation anomalies on relatively short timescales (1–6 months), whereas streamflow, reservoirs, and groundwater respond to longer-term precipitation anomalies from 6 months and up to 24 months or longer (Guttman 1999). SPI calculations shorter than 1 month or longer than 24 months may be unreliable, and statistically, 3–24 months is the best practical range of application (Guttman, 1999). Positive SPI scores indicate a greater than median precipitation, and negative scores indicate less than median precipitation (Svoboda et al., 2012). As the SPI is normalized, both wet and dry periods can be determined. Drought is defined in instances when scores are below − 1 (Table 1), and a drought is classified as having ended when SPI scores are positive (Edwards and McKee 1997).

2.4 EVI and NDVI data

The moderate resolution imaging spectroradiometer (MODIS) MOD13Q1.006 Terra Vegetation Indices 16-Day Global (Dida 2015) were used to calculate the NDVI and EVI for the time-period spanning 2000–02-18 to 2020–12-31. The MOD13Q1 V6 product provides a vegetation index value on a per pixel basis which in this dataset has 250 m resolution (Didan 2015). The NDVI is a normalized transform of the near infrared (NIR) to red reflectance ratio, designed to standardise vegetation index values between -1 and + 1 (Dindan et al. 2015). Negative values indicate water, and low NDVI values (0.1 or less) indicate barren rock or sand. Sparse vegetation such as shrubs and grasslands is likely to result in moderate NDVI values between 0.2 and 0.5 and dense vegetation such as forests is likely to result high NDVI values between 0.6 and 0.9 (Didan 2015). It is commonly expressed as:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

(Rouse et al. 1974).

EVI is also standardized, having values between − 1 and + 1 and is similar to NDVI in that it can be used to quantify vegetation greenness. The EVI makes use of the blue and red band reflectances, which makes the index less vulnerable to aerosol contamination. In general, the scattering cross section in the blue band is larger than that in the red (Didan et al. 2015). When aerosol concentration is higher, the difference between the bands becomes larger. The EVI incorporates this atmospheric resistance, and in addition, EVI decouples the soil and atmospheric influences from the vegetation signal by including a feedback term for simultaneous correction (Didan et al. 2015). The EVI formula is:

$$EVI = G\frac{NIR - Red}{NIR + C1Red - C2Blue + L} \quad (2)$$

(Didan et al. 2015).

where NIR, Red, and Blue are the full or partially atmospheric-corrected (for Rayleigh scattering and ozone absorption) surface reflectance; L is the canopy background adjustment for correcting the nonlinear, differential NIR and red radiant transfer through a canopy; C1 and C2 are the coefficients of the aerosol resistance term (which uses the blue band to correct for aerosol influences in the red band); and G is a gain or scaling factor. The coefficients adopted for the MODIS EVI algorithm are L = 1, C1 = 6, C2 = 7.5, and G = 2.5 (Didan et al., 2015).

EVI minimizes canopy background variations and maintains sensitivity over dense vegetation conditions (Didan 2015), which is especially important as the study area is predominantly covered by dense miombo woodland (Goyder et al. 2018). The MODIS NDVI and EVI products are computed from atmospherically corrected bi-directional surface reflectance that have been masked for water, clouds, heavy aerosols, and cloud shadows (Didan 2015). The products contain a detailed quality assurance bitmask, which measures the reliability of the data. Data which is considered "good" or "useful" were kept (Didan 2015), whereas data which was contaminated by clouds were removed from the analysis. The MODIS NDVI and EVI data were used to generate time series, where values were removed due to cloud contamination, missing values

Table 1 SPI scores and classification (Svoboda et al., 2012)

SPI value	Classification
> 2.0	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
− 0.99 to 0.99	Near normal
− 1.0 to − 1.49	Moderately dry
− 1.5 to − 1.99	Severely dry
≤ 2.0	Extremely dry

were replaced by the average of the values on either side of the contaminated period.

NDVI and EVI maps over the study area were produced using ArcMap 10.2. Due to the heterogeneity of vegetation coverage in the study area, vegetation indices cover three separate vegetation regions. These are (1) the highlands vegetation region which represents the entire study area; (2) the miombo vegetation; and (3) the valley vegetation. The total monthly precipitation and the monthly vegetation indices were tested for normality; all data was deemed to be not normally distributed according to the Shapiro Wilk Test ($p < 0.05$). Spearman Rank correlations between precipitation and the different vegetation regions were calculated to determine which vegetation region is more responsive to the seasonal precipitation of the area.

3 Results

3.1 Precipitation in the Angolan Highlands

The mean annual precipitation over the study area is 1113 mm for the period 1981–01-01 to 2020–12-31. The highest annual precipitation (1295 mm) is recorded in the Northwest and Northeast regions of the study area (Fig. 2). The landscape has distinct topographical features dominated by river processes; high elevations exist adjacent to low lying river valleys. Precipitation in the region is closely related to latitude and altitude. Both precipitation and altitude decrease towards the Southeast where the annual precipitation is lowest (904 mm). The CHIRPS data confirm the strong seasonality in precipitation for the Angolan highlands. For this study, we define the beginning of the wet season as the first month of precipitation occurrence following an extended dry period during a calendar year. According to the CHIRPS data, precipitation starts during September each year, reaching a peak in January (mean cumulative precipitation 231 mm/month). The wet season lasts through to April, and an almost entirely dry season lasts from May to August (Fig. 2c). The seasonality of precipitation for the Angolan highlands is applied to subsequent results.

3.2 Assessment of drought frequency

3.2.1 Drought events according to the SPI

To demonstrate the occurrence of drought at different timescales, the SPIs were calculated at 3-, 6-, 12-, and

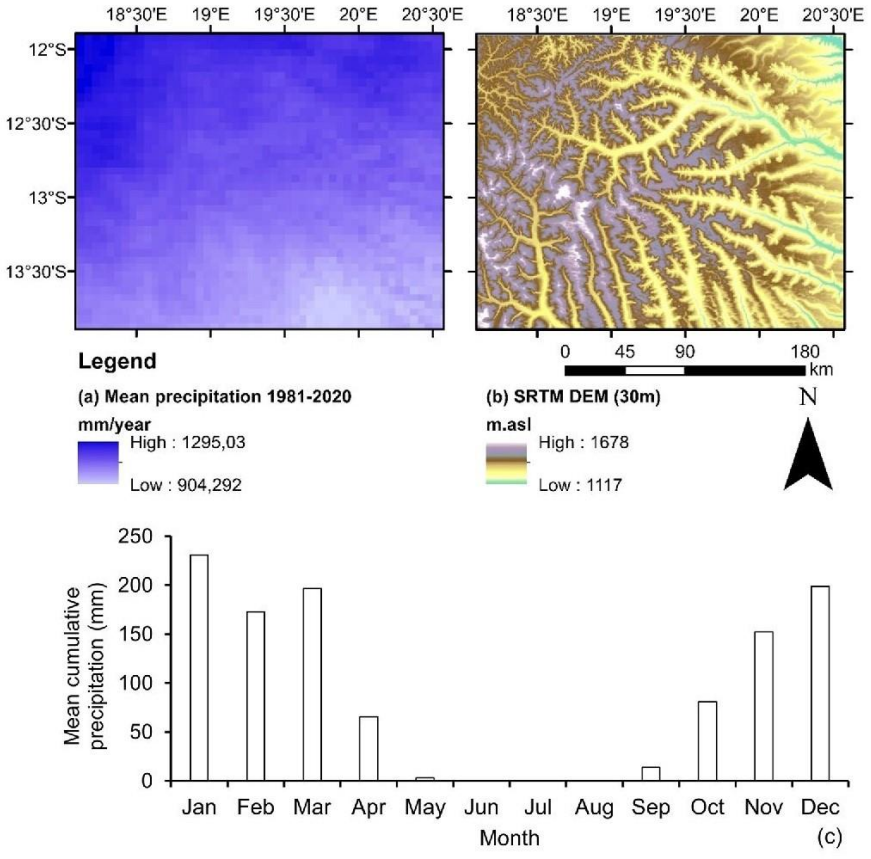

Fig. 2 **a** The mean annual precipitation (mm/year) over the study site, **b** digital elevation model at 30 m resolution, and **c** the mean cumulative precipitation (mm/month) over the period 1981–01-01 to 2020–12-31. See supplementary material Fig. 1 for the full daily precipitation time series

24-month timescales (Fig. 3). There are multiple drought events across the four timescales. For the 3-month SPI, a total of 37 drought events were recorded, 20 lasted at least three months of which three events occurred during the dry months from May to August. Three drought events lasted eight months during 1989–1990, 2014–2015, and 2018–2019, the longest drought event lasted 9 months from January 2017 to the end of September 2017. For the 6-month SPI, a total of 23 drought events were recorded, of which eight lasted at least 6 months. Two drought events were recorded for almost a full year (11 months) during 2014–2015 and 2018–2019, the longest drought event lasted 20 months from December 1995 to the end of July 1997.

For the 12-month SPI, a total of ten drought events were recorded, six lasted at least 12 months. Two 12-month drought events were recorded for 2008 and 2017–2018 and two 13-month events were recorded during 2015–2016 and 2019–2020. A 21-month long drought was recorded from February 2000 to the end of October 2001 and the longest drought lasted for 45 months from April 1994 to the end of December 1997. For the 24-month SPI, three separate drought events were recorded over the precipitation archive. The shortest lasted for 21 months starting in January 2001 and ending in September 2002 and a 45-month drought lasted from April 1995 to the end of December 1998. The longest drought event lasting 70 months started in March 2015 and ended in December 2020, at the end of the precipitation record. See supplementary material Table 1 for details regarding drought start and end months, peak SPI, and drought magnitude over each SPI timescale.

3.2.2 Drought severity

For the 40-year period under observation (1981–2020) totalling 480 months, the number of months classified as either moderately, severely, or extremely dry were calculated (Table 2). Each of the SPI calculations had a similar total number of months (ranging between 76 and 83) classified as either moderately, severely, or extremely dry. The

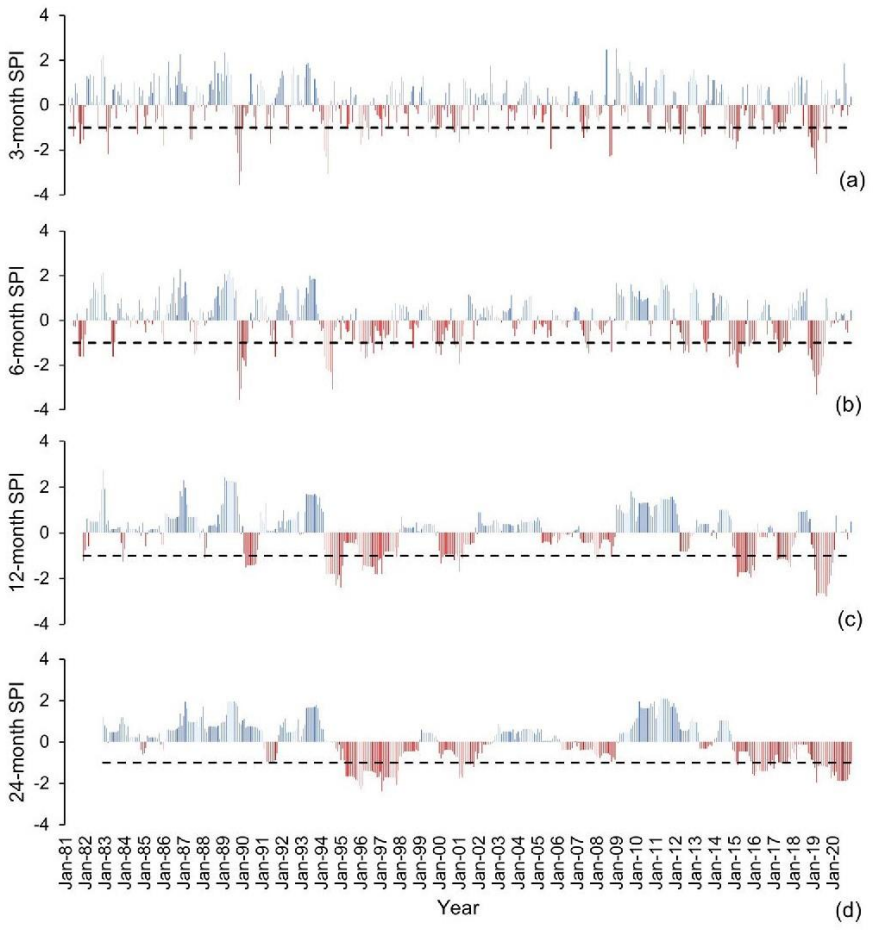

Fig. 3 **a–d** The 3-, 6-, 12-, and 24-month SPI for the period 1981–01-01 to 2020–12-31. See supplementary material Fig. 2a-b for the 36-, 48-, 60-, and 96-month SPI plots

years that had the most months of drought conditions for the 3-month SPI occurred during 1989, 2000, 2012, 2015, 2017, and 2019; the 6-month SPI during 1994, 1996, 2000, 2012, 2015, 2017, and 2019; the 12 month during 1990, 1994, 1996, 2015, 2017, and 2019; and for the 24 month during 1995–1997, 2001, 2016, 2017, and 2019 and 2020.

3.2.3 Droughts and ENSO

There are eight common periods which met the threshold SPI scores for drought (Table 3), of which five reflected droughts which overlapped over all four (3-, 6-, 12-, and 24-month) separate SPI timescales. These eight common drought periods reflect drought events that lasted at least four months and occurred at the same time for at least two of the four SPI timescales. These eight common periods occurred during 1981–1982, 1989–1990, 1994, 1995–1997, 1999–2001, 2014–2016, 2017–2018, and 2018–2019. Five of these common drought periods are longer than 12 months, making it challenging to compare them to ENSO years. Only two drought periods (1994 and 2014–2016) coincided with specific El Niño years. The longest drought (1995–1997) coincided with a range of ENSO events including a moderate La Niña (1995–1996), an ENSO-neutral (1996–1997) and a very strong El Niño (1997–1998). An extended period of dryness lasted from October 2014 to February 2020 and included three separate common drought periods (2014–2016, 2017–2018, and 2018–2020).

3.3 Vegetation dynamics of the Angolan Highlands

3.3.1 Vegetation distribution and seasonality

Vegetation in the Angolan Highlands varies spatially along the distinct topographical features on the landscape (Fig. 4). The vegetation that grows in the river valleys has lower mean EVI (0.28) and NDVI (0.37) values than the surrounding miombo vegetation (0.53 and 0.72 respectively). The indices span three vegetation regions: (1) the miombo vegetation; (2) the valley vegetation; and (3) the combination of these termed highlands vegetation. The miombo vegetation grows adjacent to the river valley environments and is commonly depicted in green in Fig. 4, valley vegetation is shown by either yellow or red in Fig. 4 owing to the differences in vegetation index scores.

The seasonality of precipitation, EVI and NDVI are similar, with NDVI and EVI for all vegetation regions being lowest at the end of the dry winter months (August), and highest during the summer rainy season (Fig. 5). Vegetation scores are shown to increase at the start of the wet season in September. Peak precipitation and peak EVI scores are both calculated for January, peak NDVI for the miombo vegetation is shown to occur during April, nearer the end of the wet season.

A Spearman rank correlation matrix was produced for the total monthly precipitation and the monthly vegetation indices over the archive (Table 4). A stronger correlation exists between EVI highlands and precipitation (0.90) versus NDVI highlands and precipitation (0.75). The strongest correlation coefficient for precipitation is with EVI valley (0.92), EVI highlands (0.90) and NDVI valley (0.88). NDVI miombo has the weakest correlation coefficients with precipitation (0.57) and the other variables. With regards to the vegetation regions, the valley region has the strongest correlation between EVI and NDVI (0.96), followed by the highlands region (0.78) and then the miombo, having the weakest correlation (0.57).

3.3.2 Vegetation response to drought

The seasonality of vegetation and precipitation is similar; however, high, or low precipitation in each rainfall season does not imply high or low mean NDVI and EVI scores respectively. Starting in September 2000 and ending in August 2020, the rainfall for each rainfall season is variable (mean of 1110 ± 91 mm/year). The driest rainfall seasons occurred during 2018/2019 (888 mm), 2014/2015 (962 mm), and 2016/2017 (1010 mm). By comparison, lowest mean NDVI scores for the highlands vegetation region occurred during 2000/2001 (0.6358), 2008/2009 (0.6365), and 2003/2004 (0.6367) and lowest EVI mean scores for the highlands vegetation region occurred during 2009/2010 (0.3275), 2003/2004 (0.3323), and 2011/2012 (0.3371).

The vegetation time series reflects that interannual vegetation dynamics are consistent with precipitation in the Angolan Highlands (Fig. 6). Low mean NDVI and EVI scores occurred at the beginning of the time series during the drought event lasting from November 1999 to October 2001 over all vegetation regions. These low vegetation scores reflected during the end of the dry seasons in August 2000 and 2001, although the decrease in vegetation scores during the dry season are not specific to drought events. The extended dry period from October 2014 to February 2020 would have potentially placed vegetation in the highlands under strain. Vegetation index scores indicate that during this period, the vegetation over all regions was able to recover at the start of each rainfall season. Vegetation recovery in the highlands was especially evident during the 2018/2019 rainfall season (888 mm, the lowest on record over the full 40-year archive) where both EVI and NDVI scores were comparatively low during the dry season but recovered at the start of the 2019/2020 season.

Table 2 Number of months classified as either moderately, severely, or extremely dry per year according to the respective SPI calculations

Year	3-month SPI				6-month SPI				12-month SPI				24-month SPI			
SPI Classification	Moderate	Severe	Extreme	Total	Moderate	Severe	Extreme	Total	Moderate	Severe	Extreme	Total	Moderate	Severe	Extreme	Total
1981	1	2	–	3	–	3	–	3	1	–	–	1	–	–	–	–
1982	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1983	2	–	1	3	–	1	–	1	1	–	–	1	–	–	–	–
1984	1	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–
1985	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1986	–	1	–	1	1	–	–	1	–	–	–	–	–	–	–	–
1987	–	2	–	2	1	1	–	2	–	–	–	–	–	–	–	–
1988	–	–	–	–	–	–	–	–	1	–	–	1	–	–	–	–
1989	1	–	3	4	–	–	3	3	–	–	–	–	–	–	–	–
1990	2	–	–	2	–	2	1	3	6	1	–	7	–	–	–	–
1991	–	1	–	1	–	1	–	1	–	–	–	–	–	–	–	–
1992	1	–	–	1	1	–	–	1	–	–	–	–	–	–	–	–
1993	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1994	–	–	3	3	–	1	5	6	–	7	2	9	–	–	–	–
1995	2	–	–	2	2	–	–	2	2	–	1	3	–	8	1	9
1996	1	2	–	3	4	2	–	6	8	3	–	11	8	2	2	12
1997	2	–	–	2	2	–	–	2	2	1	–	3	2	8	2	12
1998	1	–	–	1	1	–	–	1	–	–	–	–	–	–	–	–
1999	1	–	–	1	1	–	–	1	–	–	–	–	–	–	–	–
2000	4	–	–	4	4	1	–	5	4	–	–	4	–	–	–	–
2001	1	1	–	2	1	1	–	2	1	1	–	2	7	3	–	10
2002	1	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–
2003	1	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–
2004	1	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–
2005	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–
2006	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2007	3	–	–	3	2	–	–	2	–	–	–	–	–	–	–	–
2008	–	–	2	2	1	–	–	1	3	–	–	3	–	–	–	–
2009	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2010	1	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–
2011	3	–	–	3	1	–	–	1	–	–	–	–	–	–	–	–
2012	3	1	–	4	4	–	–	4	–	–	–	–	–	–	–	–
2013	3	–	–	3	2	–	–	2	2	–	–	2	–	–	–	–
2014	2	1	–	3	–	2	–	2	–	–	–	–	–	–	–	–
2015	3	2	–	5	7	1	1	9	2	9	–	11	1	1	–	2

Table 2 (continued)

Year	3-month SPI				6-month SPI				12-month SPI				24-month SPI			
SPI Classification	Moderate	Severe	Extreme	Total	Moderate	Severe	Extreme	Total	Moderate	Severe	Extreme	Total	Moderate	Severe	Extreme	Total
2016	1	–	–	1	–	–	–	–	–	1	–	1	10	1	–	11
2017	4	–	–	4	4	–	–	4	8	1	–	9	5	–	–	5
2018	2	1	–	3	2	1	–	3	–	–	–	–	–	–	–	–
2019	1	3	2	6	6	1	1	8	–	2	9	11	9	2	–	11
2020	–	–	–	–	–	–	–	–	1	–	–	1	2	9	–	11
Total	49	18	11	78	47	18	11	76	42	26	12	80	44	34	5	83

4 Discussion

4.1 Drought events and synoptic drivers of drought

This is the first study to analyze drought occurrence in the Angolan Highlands. The 3-, 6-, 12-, and 24-month SPIs reached drought conditions on multiple occasions over the 40 years, revealing eight common drought periods: 1981–1982, 1989–1990, 1994, 1995–1997, 1999–2000, 2014–2016, 2017–2018, and 2018–2020. The benefit of this hindsight lies in exposing the cause of these droughts to improve forecasting capability. There are large-scale synoptic systems that influence precipitation in the region. The seasonal precipitation starts during the austral winter when a heat low develops over the Bie Plateau causing advection of moist tropical westerlies from the Atlantic Ocean and the Congo Basin (Rouault et al. 2003; Cook et al. 2004; Howard and Washington 2018). Moist air from the tropical Indian Ocean is brought by the easterly trade winds resulting in a convergence known as the Congo Air Boundary (Howard and Washington 2018; Crétat et al. 2019). As summer approaches, the Congo Air Boundary migrates southward, and the heat low dissipates to be replaced by the semi-transient Angola Low (Howard and Washington 2018).

Weakening of the Congo Air Boundary during summer allows the heat low to effectively migrate southward over Namibia, removing the moisture barrier from the tropics (Howard and Washington 2018; Crétat et al. 2019). The moisture sources from the westerlies and the Congo Basin diminishes relative to the increased moisture supply from the Indian Ocean and easterlies, meaning that the Angola Low becomes the focal point of the southward development of convective systems. These mature as temperate tropical troughs (TTTs) that provide rainfall over much of the African subcontinent in the summer months (Harrison, 1984; Todd and Washington 1999; James et al. 2020). In this way, the Angola Low has a strong influence on regional precipitation across Southern Africa (Mulenga 1999). The Angola Low is centered around 13°S, 20°E (Howard and Washington 2018) directly above the Angolan Highlands study area.

Howard and Washington (2018) characterize the Angola Low as a combination of early-season heat low events (Angola heat low) and late-season tropical low events (Angola tropical low). The dry-convection Angola heat low occurs from October to November and transitions to the moist-convection Angola tropical low during December, remaining until March. The heat lows appear to be geographically locked and form only over Angola, whereas the tropical lows travel east to west across the African continent but linger at around 20°E (Howard and Washington 2018). The Angola tropical low is important for southern Africa rainfall and are dynamically similar to monsoon low

Table 3 Common drought periods according to each SPI calculation and ENSO years

Year	Drought start and end month	Duration (months)	Year-long/wet /dry season drought	Max. SPI classification, SPI overlap (max. = 4)	ENSO (year), *SST anomaly strength (NOAA, 2021, 2022)
1981–82	Oct '81–Jan '82	4	Wet	Severe, 3	Neutral (1980–1982)
1989–90	Oct '89–May '90	8	Wet	Extreme, 3	Neutral (1989–1990)
1994	Mar '94–Oct '94	8	Wet + Dry	Extreme, 3	El Niño (1994–1995), moderate
1995–97	Apr '95–Sep '97	33	Multiple year	Extreme, 4	La Niña (1995–1996), moderate. Neutral (1996–1997). El Niño (1997–1998), very strong
1999–01	Nov '99–Oct '01	24	Multiple year	Extreme, 4	La Niña (1999–2000), strong. La Niña (2000–2001), weak
2014–16	Oct '14–Feb '16	17	Year-long	Extreme, 4	El Niño (2014–2015), weak. El Niño (2015–2016), very strong
2017–18	Jan '17–Feb '18	14	Year-long	Extreme, 4	La Niña (2017–2018), weak
2018–20	Oct'18–Feb'20	17	Year-long	Extreme, 4	El Niño (2018–2019), weak. Neutral (2019–2020)

*ENSO SST anomaly strength classification: weak (0.5 to 0.9 SST anomaly), moderate (1.0 to 1.4), strong (1.5 to 1.9), and very strong (≥ 2.0: NOAA, 2021)

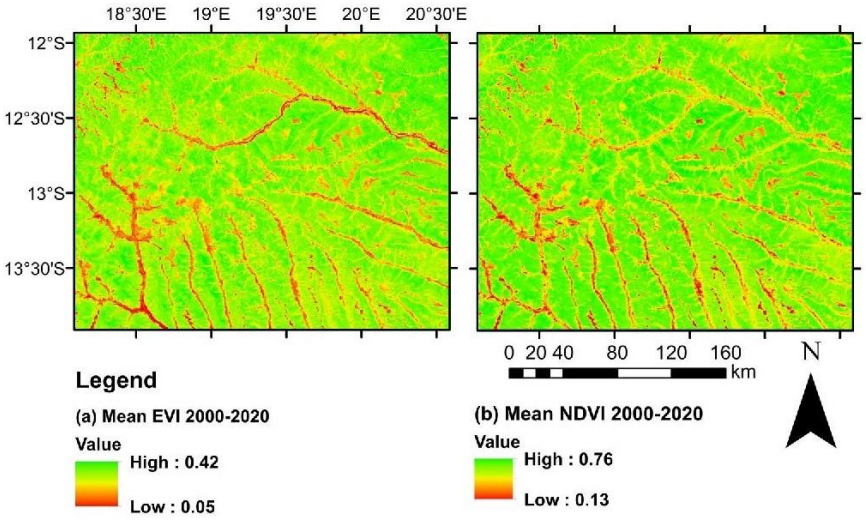

Fig. 4 Mean **a** EVI and **b** NDVI over the study area for the period 2000–02-18 to 2020–12-31

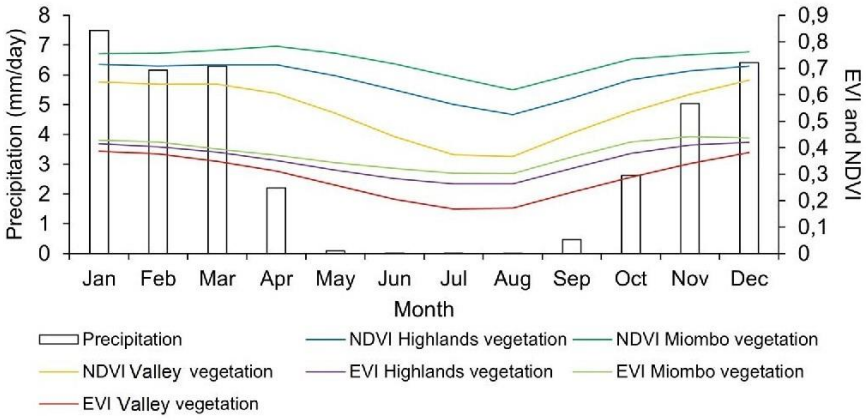

Fig. 5 The CHIRPS mean daily precipitation for each month across the Angolan Highlands study area from 1981–01-01 to 2020–12-31 and the mean NDVI and EVI for each month for the period 2000–02-18 to 2020–12-31 across the three vegetation regions

Table 4 Correlation matrix between vegetation indices and precipitation

Variables	EVI Highlands	EVI Miombo	EVI Valley	NDVI Highlands	NDVI Miombo	NDVI Valley	Precipitation
EVI Highlands	1						
EVI Miombo	0.965	1					
EVI Valley	0.947	0.874	1				
NDVI Highlands	0.780	0.683	0.861	1			
NDVI Miombo	0.642	0.571	0.708	0.925	1		
NDVI Valley	0.883	0.794	0.962	0.932	0.802	1	
Precipitation	0.896	0.842	0.918	0.750	0.565	0.875	1

All values presented are different from 0 with a significance level alpha = 0.05 ($p < 0.005$)

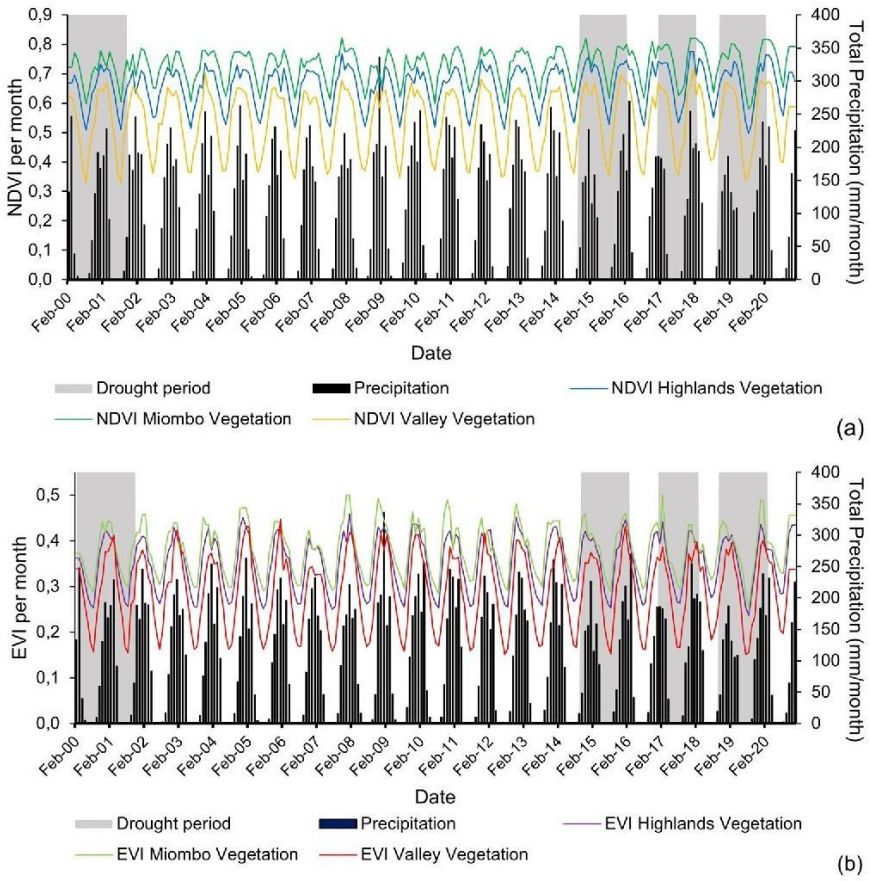

Fig. 6 **a** The mean NDVI and **b** EVI for each vegetation region per month, the total precipitation per month, and the common drought periods over the period (2000–02-18 to 2020–12-31)

pressure systems found in tropical landmasses (Howard and Washington 2018).

The El Niño phase of ENSO is typically associated with drought in southern Africa, a result of the shift in the Walker circulation (Rouault and Richard 2005). Reason and Jagadheesha (2005) found that the Angola Low may have a modulating impact on the relationship between southern Africa precipitation and ENSO. The dynamics of the Angola Low vary in intensity and location, the 1982–1983 and 2015–2016 El Niño events both occurred in years where the Angola Low was weak and resulted in severe drought over Angola (Howard and Washington 2018). The SPI results indicate that drought events over the Angolan highlands occurred before 1982–1983, in 1981–1982, and during 2014–2016. By contrast, the 1997–1998 El Niño coincided with a strong Angola Low and a drought was not observed (Howard and Washington 2018). The SPI indicates that a period of non-drought

conditions occurred between October 1997 and October 1999 over the study area. Lyon and Mason (2007) confirmed the role of the Angola Low with regards to ENSO and precipitation and found that high sea surface temperatures near southern Africa and anomalous shifts in Walker circulation contributed to the increase in precipitation in 1997–1998 as compared to 1982–1983.

The first two common drought events over the Angolan Highlands (1981–1982 and 1989–1990) occurred during ENSO neutral years. The 1994 drought coincides with a moderate El Niño event during 1994–1995 (Blamey et al. 2018; NOAA 2021), and is consistent with drought conditions over the southern African region (Rouault and Richard 2005; Tirivarombo et al. 2018). The 1995–1997 drought coincided with La Niña years, ENSO neutral years, and the 1997–1998 El Niño, which was the strongest in the twentieth century (Thomson et al. 2003; Blamey et al. 2018; NOAA 2021). The 1995–1997 drought lasting 33 months had 31 months classified as extremely dry (SPI value ≤ 2.0) for at least one SPI timescale. In southern Africa, the El Niño event of 1997–1998 was associated with an above average summer rainfall season (Blamey et al. 2018) and numerous semi-transient tropical lows over the summer months (Howard and Washington 2018). The 1997–1998 rainfall season also had above average precipitation (1130 mm vs. 1114 mm) compared to the 40-year archive for the Angolan Highlands.

Over Southern Africa, an extremely wet La Niña summer of 1999–2000 featured several tropical low events, particularly Tropical Cyclone Eline which caused devastating floods in Mozambique, Zimbabwe, and South Africa (Reason and Keibel 2004). The tropical cyclone tracked across Southern Africa from Mozambique and dissipated in eastern Namibia (Reason and Keibel 2004), evidently not influencing the Angolan Highlands as the SPI reached drought conditions lasting from November 1999 to October 2001. The 1999–2001 drought period in the Angolan Highlands is consistent with severe drought reported for Angola (Rouault and Richard 2005). However, this drought period does not coincide with other southern African countries such as Zimbabwe, Lesotho, South Africa, Zambia, and Botswana, which experienced severe drought later in 2002, 2003, and 2004, during which low crop production led to a serious threat on food security (Rouault and Richard 2005). By comparison, the SPI suggests that drought conditions did not persist into 2002 in the Angolan Highlands. The period between 2002 and 2004 was shown to have positive SPI scores, indicative of wet conditions.

The results of this study indicate that drought events have become more frequent in the Angolan Highlands over the past decade. The region suffered severe drought during 2014–2016, consistent with drought conditions in the wider southern African region (Mlenga et al. 2019), and coincident with one of the strongest El Niño events on record during 2015–2016 (Blamey et al. 2018; Kolusu et al. 2019; NOAA 2021). The regional event was the driest in the historical record (Blamey et al. 2018), which was compounded by dry conditions over the previous year (Kolusu et al. 2019). El Niño events typically lead to drier conditions during January, February, and March at the end of the summer season (Blamey et al. 2018). The SPI for the Highlands indicate that dry conditions began at the start of the rainy season in October 2014, consistent with what was identified throughout the southern African region during the 2015–2016 El Niño event (Blamey et al. 2018; Kolusu et al. 2019). The contrasting rainfall patterns and inconsistent connection between El Niño events and southern African climate is well documented (Boulard et al. 2013; Blamey et al. 2018), and the evidence from the Angolan Highlands is similarly erratic.

Droughts do not necessarily fall into single seasons and droughts typically end during the wet season (Luetkemeier and Liehr 2019). The dry months of 2017 (May through August) during the drought from January 2017 to February 2018 were classified as moderately dry, while positive scores for March 2018 signal that the drought terminated late in the rainfall season. Dry conditions were exacerbated by low precipitation over the next rainfall season, and another extreme drought started in October 2018. During 2019, it was documented that the southern provinces of Angola had one of the driest seasons since at least 1981 (RVAA, 2019). This is consistent with the average precipitation per rainfall year across the Angolan Highlands, where the 2018–2019 rainfall season (888 mm) was the lowest on record over the full 40-year archive. This recent drought event has had serious implications on food security and health in the southern provinces of Cunene, Hulia, and Namibe (RVAA 2019), and the SPI demonstrates that this was a widespread phenomenon extending to the Angolan Highlands.

4.2 Drought implications

NDVI and EVI historical data were used to assess the impacts of precipitation deficits on vegetation over the Angolan Highlands. EVI minimizes canopy background variations and maintains sensitivity over dense vegetation conditions (Didan 2015), whereas NDVI tends to overestimate vegetation growth over densely vegetated areas and is also sensitive to underlying soil colour (Gao et al. 2020). EVI is more strongly correlated to precipitation than NDVI in the region, potentially caused by overestimation of miombo vegetation over certain months by the NDVI. The heterogenous vegetation cover led to the analysis of three different vegetation regions: the highlands, miombo, and valley vegetation. The miombo woodlands contain over 8500 plant species, provide habitat for wildlife, and support millions of people who are dependent on the woodlands for their livelihoods

(WWF 2021). NDVI for miombo vegetation has the weakest correlation with precipitation, and the seasonality suggests that miombo vegetation reaches greatest productivity in April, 3 months after the wettest month suggesting a lag time in miombo productivity.

Valley vegetation for both NDVI and EVI has the strongest correlation to precipitation. The valley environment supports extensive riparian vegetation including wet grasslands, peatlands, and oxbow lakes (Conradie et al. 2016; Goyder et al. 2018). Lourenco et al (2022) describe the peatlands as minerotrophic, a distinct seep-line exists parallel to the higher ground (dominated by miombo vegetation) adjacent to the valley region, the seep-line is an inflow area of ground water, and peatlands persist where there are physical features that pond this water. The valley environment is often patchy, having less peatland cover in comparison to much larger expanses of grassland (Lourenco et al. 2022). The seasonal response of valley vegetation suggests that areas that are not ponded are dependent on precipitation, having a similar seasonal pattern to precipitation.

The strong correlation between vegetation indices and precipitation demonstrates the potential risks to regional vegetation during periods of drought. During 2019, the Angola Vulnerability Assessment Committee mention that the drought caused loss of livestock and low crop yields in the southern provinces of Angola (RVAA 2019). It was estimated that 1.14 million people were food insecure in the southern provinces of Namibe, Cunene, Cuando Cubango, and Huila alone, and it is likely that the subsistence communities in the Angolan Highlands experienced the same hardships. Total precipitation and drought frequency are important factors in determining total greenness for a given time, but they do not operate in isolation. Despite the results indicating that drought events have become more frequent in the Angolan Highlands over the last decade, it is possible that vegetation growth may be enhanced by CO_2 fertilization and improved water efficiency as documented in tropical, woodland and savanna biomes across southern Africa (Midgley and Thuiller 2011; Jin et al. 2013; Geremew et al. 2022).

The threat of drought to the Angolan Highland landscape is further exacerbated by anthropogenic practices. The miombo vegetation is cleared for timber and the valley environment is used for cultivation through peatland drainage, peat fuel is also extracted, and grassland areas are used for grazing and often burned (Conradie et al. 2016; Taylor et al. 2018). Significant societal impacts are common amongst food-scarce developing countries with high dependency on agriculture (Ahmadalipour et al. 2019). Increased drought occurrence could have major impacts in a region that is heavily dependent on natural resources. Continued population growth, lack of financial support, subsistence agriculture, and human pressure on the land are increasing in unprotected, rural areas of Angola (Catarino et al. 2020), such as the Angolan Highlands. The rural population of Angola comprises 11.1 million people, or 37% of the total population (RVAA 2019). According to the International Trade Administration (ITA), in 2018, agriculture accounted for 11% of the country's GDP, supporting both informal and formal employment of 30% of the Angolan population (ITA 2021). Potential environmental degradation can be expected from the combination of drought and anthropogenic pressures. This will require adaptation strategies in future, especially concerning water resources and agricultural practices.

4.3 Threats of climate change

Angola is highly vulnerable to climate change (Brooks et al. 2005). Climate variability in the Angolan Highlands region is one of the strongest drivers of rainfall variability over a subcontinent (Crétat et al. 2019). The trends in SPI scores indicate negative gradients towards drier conditions over all timescales. Over the archive, drought return rates are variable but have increased during the last decade, as three separate drought events occurred since 2014. This data is consistent with other studies for Angola, both stronger and more frequent droughts are expected through the next century (Brooks et al. 2005; Cain 2015; Carvalho et al. 2017). Due to the paucity of monitoring networks, studies of climate projections in Africa rarely include Angola, the majority of which provide an evaluation of different regional climate models (RCMs) over multiple countries (Carvalho et al. 2017).

Carvalho et al. (2017) compared four RCMs with data from 12 meteorological monitoring stations specifically in Angola. The study presented scenarios of future temperature and precipitation anomaly trends and the frequency and intensity of droughts for the twenty-first century. While there is a difference in the performance of the four RCMs, particularly for precipitation, consistent results were found for temperature projections, with an increase of up to 4.9 °C by 2100 (Carvalho et al. 2017). The temperature increases are lowest for the northern coastal areas and highest for the southeast areas (nearer the study site). In addition to increased temperatures, Angola is predicted to face heat waves lasting between 60 and 120 days every 2 years under the RCP8.5 (business as usual) scenario (Dosio 2017). In contrast to temperature increases, precipitation is projected to decrease by 2% on average for the country. Once more, the strongest projection was for the southeast, with decreases of up to 4% (Carvalho et al. 2017).

Using the 6- and 12-month SPI data and RCMs, Carvalho et al. (2017) concluded that climate change in Angola will bring stronger and more frequent droughts (consistent with the SPI data for the Angolan highlands) through the century, with impacts on water resources, agricultural productivity, and wildfire potential. Mendelsohn (2019) describes the current challenges to land transformation and degradation in

Angola that are likely to increase in future (Carvalho et al. 2017; Huntley et al. 2019). The need for fuel sources reduces plant cover, resulting in lower volumes of rainwater being trapped or impeded, thus reducing seepage into the topsoil to replenish soil moisture and recharge local aquifers (Mendelsohn, 2019; Huntley et al. 2019). With lower soil moisture, seepage to sustain river flows during the dry season also declines (Huntley et al. 2019). As precipitation affects productivity, this will have influence on the subsistence farming strategy, and crop production. This may be the reason for increased farming of peatlands which are an important carbon sink and water flow regulator (Lourenco et al. 2022), leading to further environmental degradation.

The lack of reliable climate data for Angola from the past 40 years is a challenge for climate change research (Huntley et al. 2019). The Angolan Highlands are hydrologically and ecologically important but continue to remain unprotected (Quammen 2017). It is a major source water region for three major river catchments (Congo, Zambezi, and Okavango), supporting transboundary rivers that flow into six southern African countries (Namibia, Botswana, Zambia, the Democratic Republic of the Congo, Mozambique, and Zimbabwe) and is the only source region of the Okavango Delta (Marazzi et al. 2017; Yurco et al. 2017). Drought events occurring in the region are likely to be far reaching, affecting human and ecological welfare downstream. The rivers originating in the highlands continue to flow unimpeded but future pressures on water resources and projected population increases are likely to aggravate dwindling freshwater reserves in southern Africa. Synoptic drivers of precipitation in the region have only recently received strong attention (Howard and Washington 2018; Crétat et al. 2019). Future work in monitoring and protecting the highlands will have strong implications for water budgets across southern Africa.

5 Conclusion

This study integrates precipitation data and vegetation indices in an historical assessment of drought in the Angolan Highlands. Drought occurrence has increased over the last four decades, with three drought events occurring since 2014. The SPI data indicates that most of the drought periods were regional. The relationship between drought occurrence and ENSO is not linear. A strong positive correlation exists between vegetation and precipitation, with EVI having the stronger correlation over NDVI and precipitation. The valley vegetation has a stronger correlation with precipitation compared to the miombo vegetation, reflecting the same seasonality as precipitation. The observed SPI time series exhibited a downward trend during the past 40 years. Although 40 years is a relatively short period with regard to decadal and multi-decadal climate variability, this could support the notion that drought occurrence and frequency will increase in future as determined in other studies. Drought incidence and severity should be carefully monitored, representing a key future avenue for climate modelling research in the region. Despite the significant ecological importance of the Angolan highlands, the region remains unprotected. The Angolan population is reliant on rain-fed agriculture, adaptive measures, especially for water resources are required to mitigate the impacts of future drought events.

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CHAPTER 7: FIRE REGIME OF PEATLANDS IN THE ANGOLAN HIGHLANDS

7.1 Brief synopsis

Using MODIS fire and vegetation data in combination with the LULC map presented in Chapter 5, this study presents the first assessment of the contemporary fire regime of peatlands in the Angolan Highlands. Fire and associated degradation have been extensively documented in tropical peatland deposits in southeast Asia, with little to no reporting for African tropical peatlands. This is an important contribution as the study provides a first assessment of the fire regime of peatlands, including the implications of fire for peatlands, and discusses fire management, future research, and area conservation for the Angolan Highlands.

Author contributions:

Contributor role	**Author contribution**
Conceptualisation	Lourenco M, Fitchett JM, and Woodborne S
Methodology	Lourenco M, Fitchett JM, and Woodborne S
Validation	Lourenco M
Formal analysis	Lourenco M
Investigation	Lourenco M
Resources	Lourenco M
Data curation	Lourenco M
Writing – the original draft preparation	Lourenco M
Writing – review and editing	Lourenco M, Fitchett JM, and Woodborne S
Visualisation	Lourenco M
Supervision	Fitchett JM and Woodborne S
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Lourenco M – 75%

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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 km^2 (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 km^2) 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 km^2 within an area spanning 61,590 km^2 (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; Vetrita & 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 interannual 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 southeast 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 km^2. 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

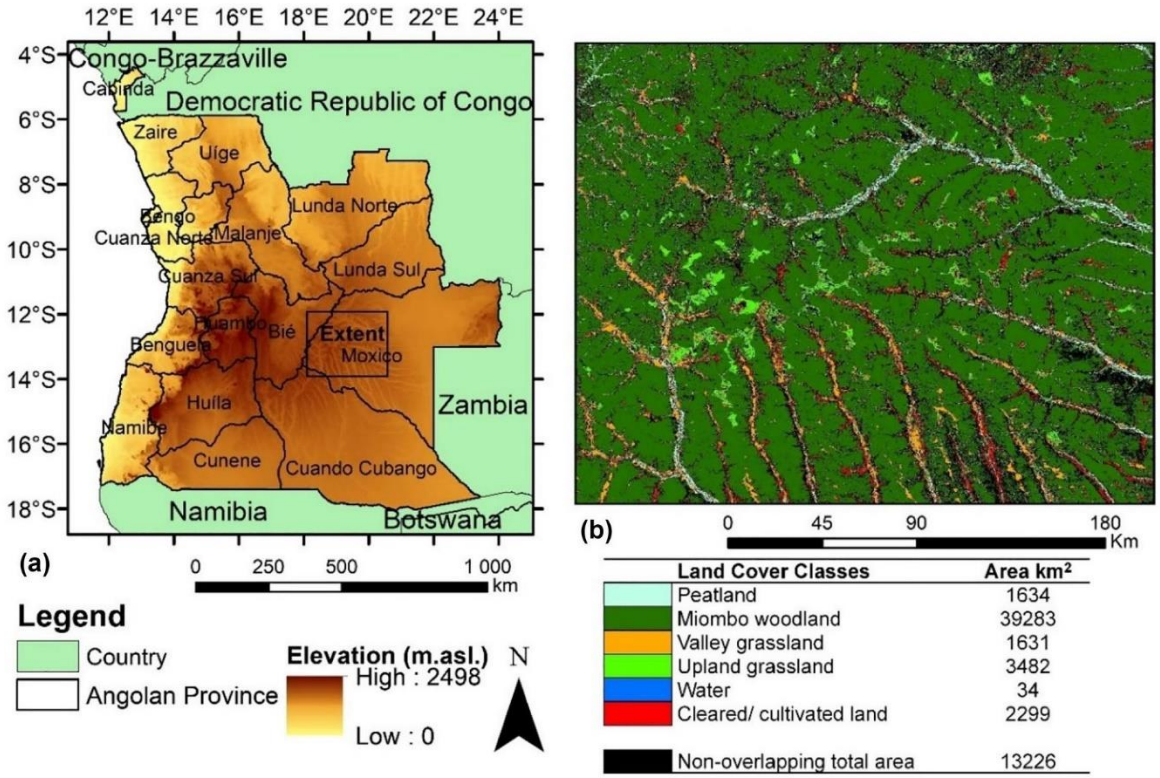

Fig. 1 **a** Study area map showing the study site extent in Angola and **b** the LULC of the study area

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 km^2) compared to other products (Katagis & Gitas, 2022), and has comparable accuracy in detecting tropical peatland fires (Vetrita 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 km^2. 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 km^2 (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 km^2 (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 km^2 (22.36%) of the total land surface area. For the remaining 6976 km^2 (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 km^2 of the study area was burnt from 01/01/2001 to 12/31/2020, at an average of 11,011 km^2 (SD. 2999 km^2) per year (Fig. 4). The lowest burn areas were calculated for 2001 (5024 km^2 or 8.14% of the study area), 2020 (5988 km^2 or 9.71%), and 2002 (6413 km^2 or 10.40%), and the largest burn areas were calculated for 2019 (16,889 km^2 or 27.38%), 2017 (15,652 km^2 or 25.37%), and 2011 (13,953 km^2 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).

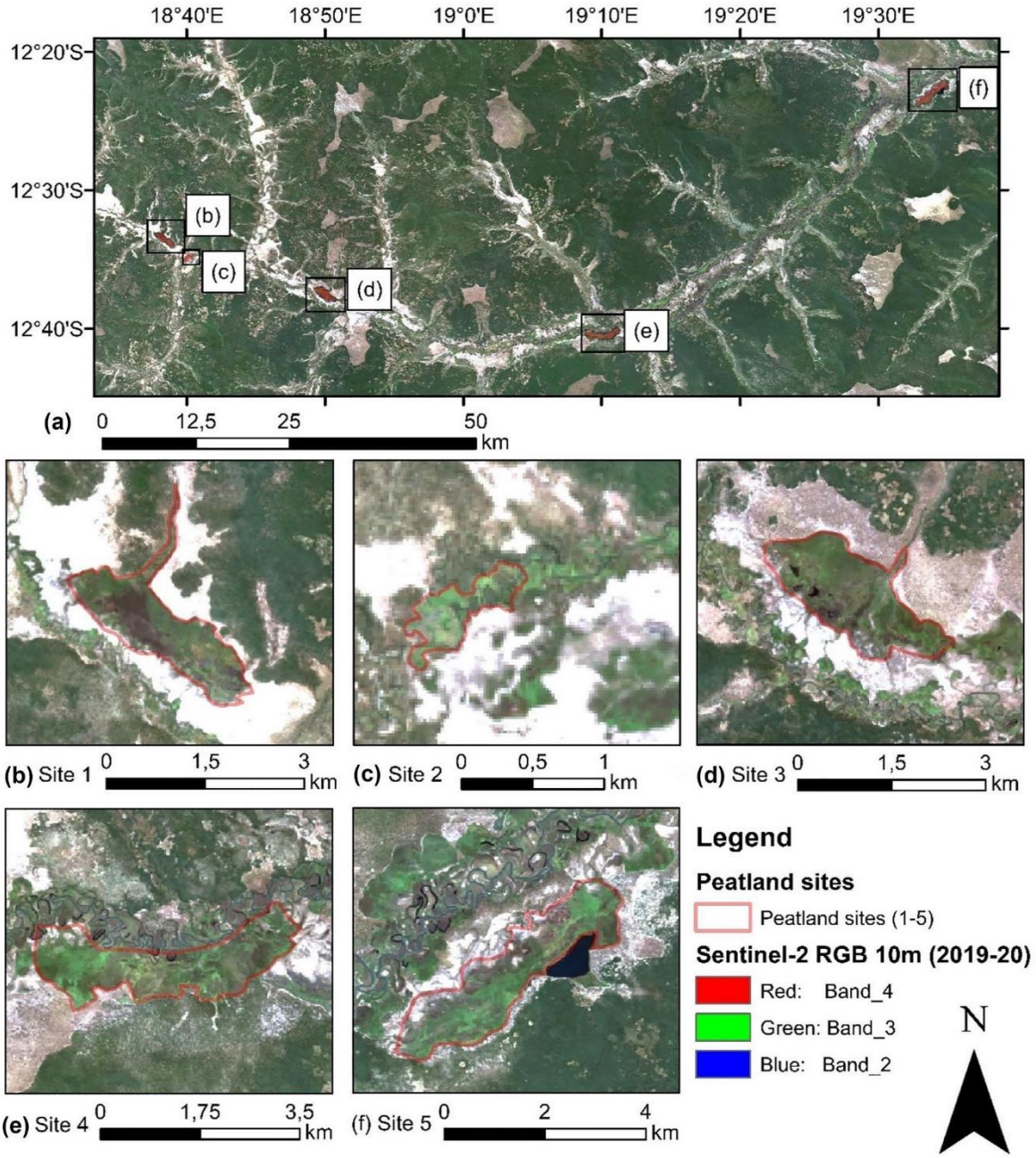

Fig. 2 Peatland sites 1–5 along the Lungu Bungu River

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

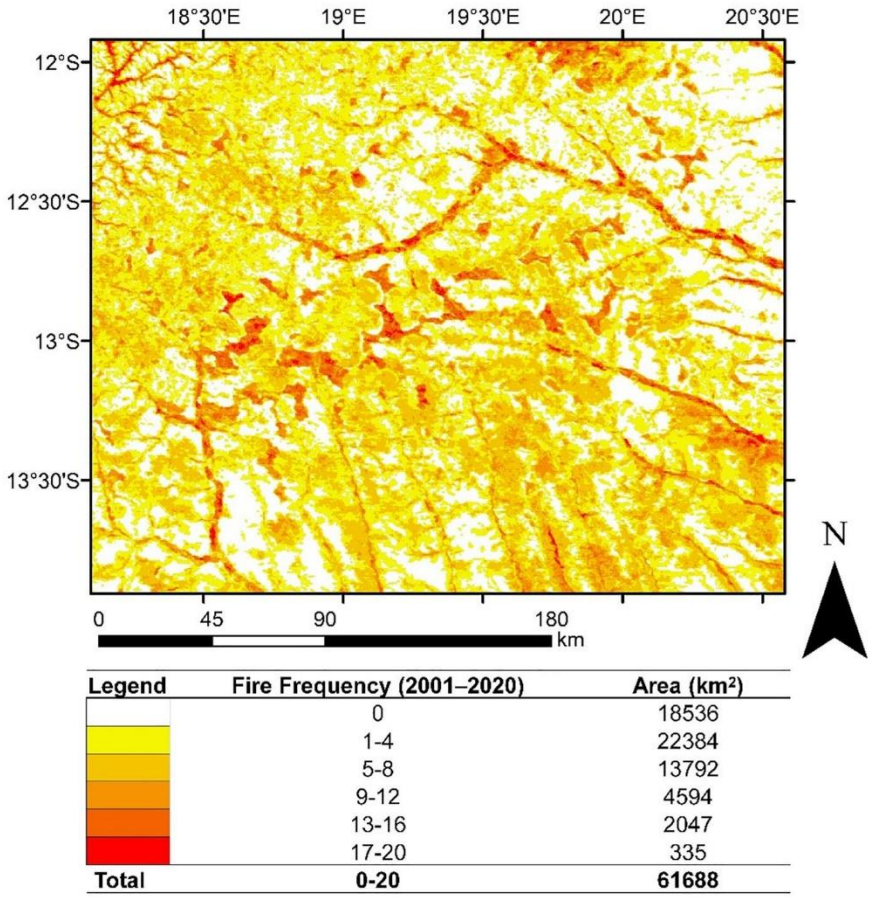

Fig. 3 Fire frequency per pixel over the period 01/01/2001 to 31/12/2020 at 250 m resolution

peatland, but this is due to these LULC classes having a larger total classified area. On average, 746 km^2 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 km^2), 2017 (52.58% or 859 km^2), and 2005 (50.83% or 831 km^2: 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 km^2 per year of

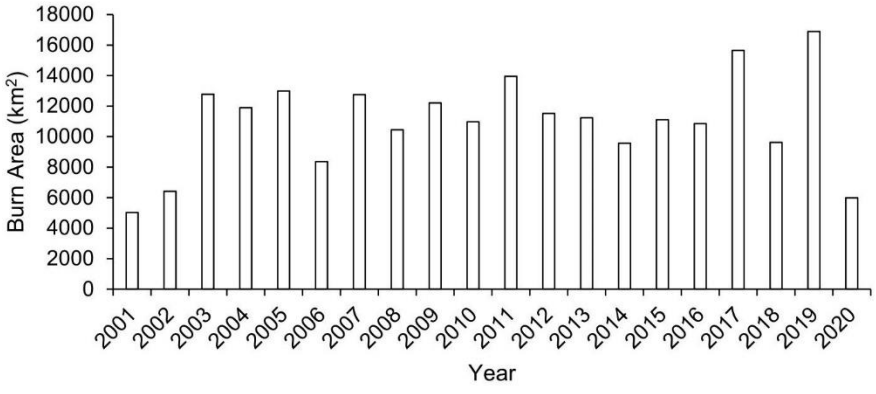

Fig. 4 Burn area per year for the study site over the period 01/01/2001 to 31/12/2020

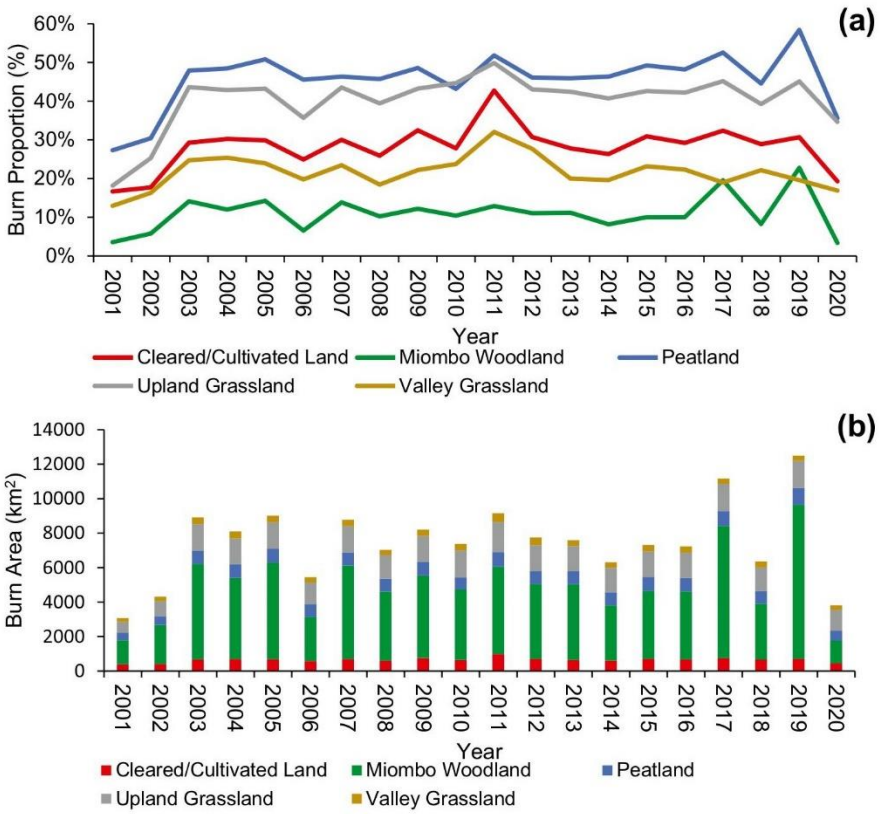

Fig. 5 **a** Burn proportion and **b** burn area per year for each LULC class over the period 01/01/2001 to 31/12/2020

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 km^2) and 2017 (18.96% or 7680 km^2), 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) for the peatland class and the lowest for the miombo woodland class (2.20 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

The peatland class had the smallest proportion (4.11% or 67 km^2) of area that did not burn once and had the largest proportion (6.07% or 99 km^2) 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 km^2 and 26.70% or 436 km^2 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.

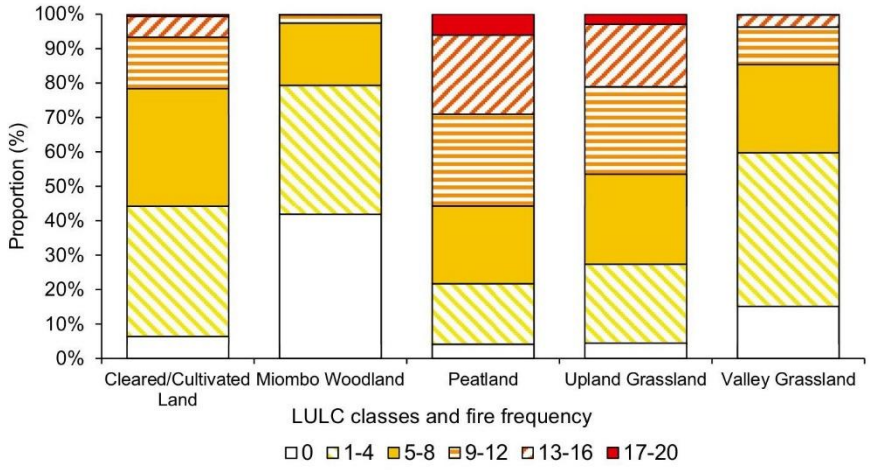

Fig. 6 Proportion of area having specific fire frequencies for each LULC class

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 km^2) and August (195 km^2) for peatland. Miombo woodland had the highest average burn area during August (1,308 km^2) and September (2,477 km^2). 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 km^2) and August (169 km^2).

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 FireCCI51 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, Vetrita 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 (Vetrita & 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

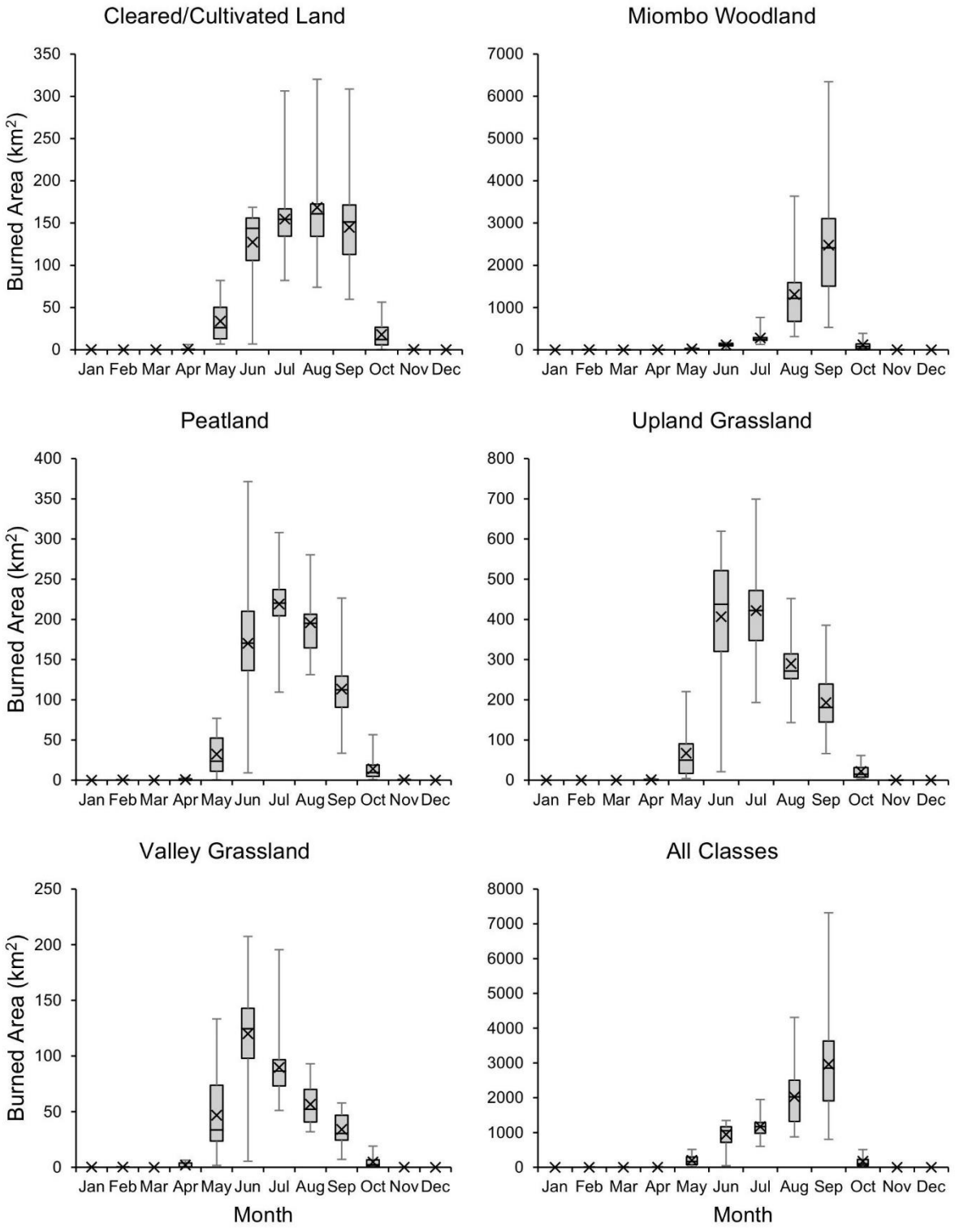

Fig. 7 Box-and-whisker plots of the maximum, minimum, average, mode, and inter-quartile range of the annual burned area for each LULC class and all classes per month from 2001 to 2020

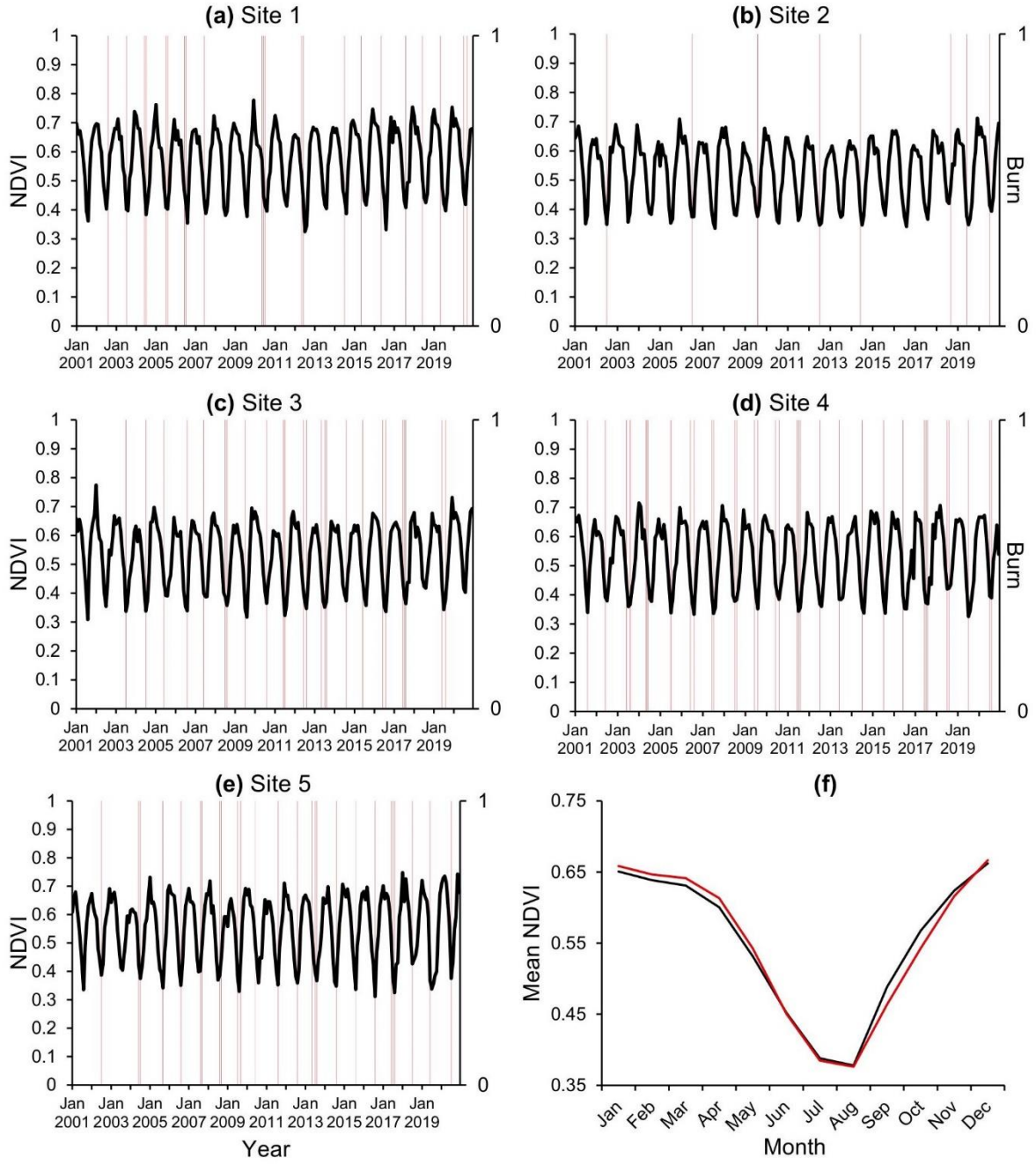

Fig. 8 Peatland vegetation (average NDVI per month) and burn history (2001–2020) for sites 1–5 (**a**–**e**). The black line indicates the time series of average NDVI for each month, a burn value of 1 (red vertical line) corresponds to the month in which the peatland burnt. In some instances, fires occurred over multiple 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; Vetrita & Cochrane, 2019). Peatlands rarely burn due to waterlogging (Rieley & Page, 2016), but desiccated peat is inherently combustible (Vetrita & 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; Vetrita & 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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CHAPTER 8: GENERAL DISCUSSION

8.1 Introduction

This chapter presents the general discussion, divided into three themes cross cutting the four research papers (Chapters 4-7), namely peat preservation in the Angolan Highlands, environmental change in the Angolan Highlands, and concerns for the Angolan Highlands region. In addition, this chapter integrates and expands on the findings and connections between each research paper with reference to literature. During the PhD, Chapter 5 was the first to be published, followed by Chapter 4. Chapters 6 and 7 were in review at the same time and published shortly after one another. Although having similar vegetation, precipitation, and fire time-series records, the journal articles that appear in Chapters 6 and 7 were submitted as standalone research papers. A discussion of the limitations of this study is included in this chapter.

8.2 Peat preservation in the Angolan Highlands

Peatlands have been identified in at least 175 countries, occurring in polar and tropical regions and every climatic zone (Lindsay, 2010; Bain et al., 2011; IPS, 2020). Due to available resources and widespread peatland coverage, peatlands have been mapped extensively in the northern hemisphere; however, shortfalls exist in adequate peatland distribution maps both for the southern hemisphere and the tropics (Page et al., 2011; Evans et al, 2014). As a result, the dissemination of global peatland distribution maps is biased towards the northern hemisphere (Wu et al., 2017; Xu et al., 2018). Global peatland maps and estimates of peatland extent are also inconsistent as they are produced from several differing data sources at global, regional, and national levels

(Wu et al., 2017; Xu et al., 2018). These collection approaches are both dependent and constrained to high quality peatland extent data that are only available for a small selection of countries and regions, including Canada, Sweden, and West Siberia (Wu et al., 2017).

The first peatland map of the Angolan Highlands (Chapter 5) provides a conservative estimate (1,634 km^2) of peatland extent for the region. The best estimate (2,640 km^2) of peatland extent for Angola reported by Page et al. (2011) makes no mention of these deposits, and it is likely that the estimate is an addition to peatland extent reported for Angola. This estimate is a crucial first step in providing the peat carbon inventory and facilitates conservation efforts for the region and surrounding basins. In addition, it provides updated peatland data for Angola that may be used in updated estimates of global peatland extent.

Peatlands store more carbon than the above-ground carbon stored in all the world's forests (Page et al., 2011; Bain et al., 2011). Despite this, peatlands have received less attention under the UNFCCC (Ramsar, 2002; Evans et al, 2014), and have only recently received substantial recognition at the 2021 UNFCCC COP26 (IUCN, 2021). The focus of the literature over the last decade has steered toward peatland preservation (Finlayson and Milton, 2018; Rieley and Page, 2016). This is facilitated by accurate classification of peatland extent (Minasny et al., 2019; FAO, 2020) and quantification of peatland carbon (Law et al., 2015; Xu et al., 2018). In Chapter 4, the study extends this focus, stating that discrepancies in peat and peatland definitions are negatively influencing efforts in quantifying global peat carbon stock. In this study, a new definition for peatland is proposed, motivated by climate science, preservation,

and carbon accounting. The implication is that a common definition for peat and peatland will also contribute towards its preservation. Chapter 5 does not include the conservative definition proposed in Chapter 4 as it was written and accepted before the comprehensive review of peat and peatland definitions.

There are several anthropogenic practices that threaten the preservation of the Angolan Highlands peatland deposits, including extensive fires, slash and burn agriculture (also known as shifting agriculture), peat fuel extraction, wetland drainage, and overgrazing (Conradie et al., 2016; Taylor et al., 2018). As calculated in Chapter 7, the peatlands burn more frequently, have the smallest proportion of area which does not burn, and have the largest average proportion of burnt area per year among all the LULC classes. Peatland functioning is dependent on continual recycling of organic matter under waterlogged, anaerobic conditions (Lawson et al., 2015). Conditions where either vegetation is removed, or the water table is lowered are major threats to peatland growth and functioning (Rieley and Page 2016).

Human interference on peatlands can be highly detrimental (Brevik and Homberg, 2004; Hooijer et al., 2010) as drainage, peat extraction, inappropriate burning, and conversion to agriculture all lower the water table (Bain et al., 2011; Page et al., 2011). The more intensively the peatland is disturbed, the quicker the peat degrades, oxidises and releases GHGs (Bain et al., 2011; Evans et al., 2014; Lawson et al., 2015). Compromised peatlands become a major source of GHG emissions which may continue for many years until all the peat is lost (Joosten 2011; Bain et al., 2011). The combination of extensive area covered by peatlands and potential long-term emissions makes the climate effect of degraded peatlands fundamentally distinct from other

ecosystems (Joosten 2011; Bain et al., 2011), requiring consistent monitoring and unique preservation strategies (FAO, 2020).

Peatlands are sensitive to temperature, precipitation, and prolonged periods of drought (Belyea and Malmer, 2004). In Chapter 6, drought events in the region are shown to increase through time and negative SPI trends indicate that drought occurrence and frequency are likely to increase in future. The vegetation response to drought was calculated for the study area, and more specifically for the vegetation within the valley environment which contains much of the peatlands classified in Chapter 5. Under drought conditions, both soil moisture and the water table decrease, facilitating the increased potential for aerobic respiration, causing peatlands to become net sources of CO_2 (Fenner and Freeman, 2011; Lund et al., 2012; Jassey et al., 2018). The relationship between drought and ecosystem response is often non-linear (Jassey et al., 2018), however, tipping points have been identified for individual peat forming species in response to drought, when reached these thresholds that are detrimental to the ecological functioning of the peatland (Lund et al., 2012; Lamentowicz et al., 2019).

Peatlands rarely burn when waterlogged (Rieley and Page, 2016), however, if desiccated due to drought and or drainage, they are more easily combustible (Vetrita and Cochrane, 2019). Peatland loss and degradation due to the combustion of deeper peat has been documented in boreal and tropical peatlands across the globe (Rieley and Page, 2016; Turetsky et al., 2015). The results presented in Chapter 7 suggest that peatland burning within the five intact peatland sites are surface vegetation fires, where the above-ground peat forming vegetation is burnt and recovers shortly after

burning. Smouldering (deep peat) fires would likely result in peatland degradation (Vetrita and Cochrane, 2019), where the surface vegetation would not be able to recover post burn and continue to burn year on year. It is critical that these peatlands remain undisturbed and are protected because they have a natural resistance to smouldering combustion and degradation, protecting the deeper peat layers that have accumulated carbon over thousands of years. Within undisturbed peatlands throughout the world, most of the peatland carbon stock is typically protected from smouldering, but drying because of human activity, drought and climate change lowers the water table, exposing the deeper peat to smouldering combustion and degradation (Vetrita and Cochrane, 2019).

According to Regional Climate Models (RCMs) for Angola, the Angolan Highlands are projected to become both drier (decrease in precipitation of up to 4%) and warmer (increase in air temperature of up to 4.9 °C) by 2100 (Carvalho et al., 2017). Continued population growth, subsistence agriculture and human pressure on the land are increasing in unprotected rural areas of Angola such as the Angolan Highlands (Catarino et al., 2020). Local communities are likely to target the moist and organic rich peatlands for cultivation in a warmer and drier climate future (Humpenöder et al., 2020), lowering the water table and exposing deeper peat to fire and degradation. Multiple countries have developed national peatland strategies to promote preservation to ensure continued functionality (Andersen et al., 2017). Standard peatland management practices include the promotion of peat forming vegetation, prevention of water loss and water pollution and reduction of peat extraction, cultivation, and drainage (Dohong et al., 2017). Context-driven strategies should be

considered with the input of local ecological and indigenous knowledge, communities, and stakeholders (Van Noordwijk et al., 2014; Fleming et al., 2021).

8.3 Environmental change in the Angolan Highlands

Over the last decade, unprecedented changes in the human and biophysical environments have occurred (Loisel et al., 2021). These include the increase of fossil fuel emissions and rising global temperatures, which place greater importance on carbon sinks (Friedlingstein et al., 2019). Reducing the atmospheric abundance of carbon dioxide (CO_2) and other GHGs is required to mitigate the risks of climate change (Houghton, 2002; Archer et al., 2009). Peatlands contribute towards this mitigation as they are an important natural reservoir of global carbon (Ramsar, 2002). In the 6th Assessment report of the IPCC, a headline statement (high confidence) states that: “Under scenarios with increasing CO_2 emissions, the ocean and land carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere” (IPCC, 2021: 36). Under the SSP1-1.9 (very low GHG emissions) scenario, the total cumulative CO_2 emissions taken up by land and ocean is projected to be 70% in 2100 (remaining 30% stays in the atmosphere). However, under the SSP5-8.5 (very high GHG emissions) scenario, this uptake reduces to 38% as ocean and land carbon sinks become less effective, meaning that there is likely to be a higher proportion of emitted CO_2 remaining in the atmosphere (IPCC, 2021).

In Chapter 5, AMS radiocarbon dates of these peatlands reveal that peatland initiation began at least ~ 7100 cal. yr BP; the implications are that these deposits may store a significant amount of carbon and have the potential to be an important part of the global carbon budget (Goyder et al., 2018). If these peatlands are disturbed or

degraded, carbon intake will be reduced, ultimately intensifying CO_2 concentrations and further contribute to climate change, influencing the deposits in a negative, self-perpetuating cycle (Brevik and Homberg, 2004; Joosten 2009, 2011). In addition, if strong mitigation took place and GHG concentrations in the atmosphere were drastically reduced below current levels, historical emissions of long-lived GHGs will remain significant to future contributions of warming due to past accumulation and the inertia of the climate system (Skeie et al., 2021), and continue to impact these peatlands in future. Therefore, initial monitoring and preservation of the deposits are necessary in an uncertain climate future that depends on intact, natural carbon sinks (Friedlingstein et al., 2019).

Peat is a soil distinguished from other soil types owing to the build-up of organic matter due to the combination of plant growth and waterlogging (Lindsay, 2010). Peat is therefore a direct product of the vegetation growing on the surface, reflecting prevailing hydrological and nutrient conditions controlled by climate and underlying landforms (Lindsay, 2010; Bain et al., 2011). In Chapter 6 and 7, valley vegetation EVI and NDVI and peatland NDVI indicated that vegetation growth has the same seasonality as the precipitation in the region. The implications are that vegetation occurring in the valley environment (which supports most of the peatland deposits classified in Chapter 5) is more strongly correlated with seasonal precipitation, and its growth is hydrologically dependent.

Chapter 6 demonstrates that the Angolan Highlands vegetation was buffered against the drought periods that occurred since 2001. The NDVI and EVI timeseries indicates that the valley vegetation, which supports the peatlands, recovered at the start of each

rainfall season, a pattern which was identified even after the driest rainfall season on record during 2018/2019. In addition, although Chapter 7 did not include the drought data obtained from Chapter 6, the NDVI timeseries of the five intact peatland sites does overlap these drought periods. The peatland NDVI timeseries provide further evidence that the peatland vegetation is buffered against drought conditions, recovering at the start of each rainfall season even during drought periods. It is important that these peatlands remain undisturbed, as human activities would likely contribute to peatland degradation, limiting the peatland natural resistance to both drought and fire.

In comparison to the valley vegetation region, miombo vegetation has peak greenness three months after peak precipitation. The ecological importance of the miombo woodlands cannot be overstated (Chiteculo and Surovy, 2018). The precipitation which falls on the upland environment, covered by Kalahari sand, is buffered by the miombo, and it is the interaction between the groundwater filtering through the sand and the adjacent seep line that allows and sustains peatland growth in this region, a mechanism for peat growth that has likely been present for millennia. In addition, the peatlands limit river flow and are a control valve between groundwater flow and the river as described in Chapter 5.

The use of RS datasets provides contemporary environmental change indicators in a region which is historically war stricken and has had limited accessibility for scientific research (Conradie et al., 2016; Midgley and Engelbrecht, 2019). Chapters 6 and 7 demonstrate both direct and indirect anthropogenically induced environmental changes in the landscape. Over the 20-year fire record (2001-2020) presented in

Chapter 7, four common drought periods were identified within Chapter 6, of which three occurred since 2014. The two highest (2017 and 2019) annual burn area totals for the study area coincide with the 2017-2018 and 2018-2020 droughts, with 2019 having both the lowest seasonal rainfall total and highest burn area on record since 1981 and 2000, respectively.

Increased burn area is likely due to the increased volume of dry material across the landscape, making fires more prevalent during periods of low rainfall and drought (Laris et al., 2016). Although fire occurrence could not be directly attributed to humans, the total burn area across the region highlights the potential influence of rural communities on fire, with an increase in burn area during 2003 following the end of the Angolan Civil War and a decrease during the 2020 lockdown associated with the COVID-19 pandemic. Precipitation deficits accounted for in the last 40 years indicate that rainfall has a negative trend, with the possibility of increased drought occurrence in future, consistent with what has been documented in Angola (Brooks et al., 2005; Cain, 2015; Carvalho et al., 2017) and throughout southern Africa (Abiodun et al., 2019; Nhamo et al., 2019; Gore et al., 2020). As a result of anthropogenic climate change, southern Africa, a region that is already characterised as dry and hot (Geppert et al., 2022), is projected to become generally drier under low-mitigation climate futures (Archer et al., 2018).

8.4 Concerns for the Angolan Highlands region

Temperatures over southern Africa have increased rapidly over the last five decades, at a rate of near twice the global rate of temperature increase (Archer et al., 2018;

Gore et al., 2020). Under low-mitigation futures, further increases, up to 6°C by the end of the century relative to the present-day climate, may occur over the central and western interior regions (Engelbrecht et al., 2009; Archer et al., 2018; Abiodun et al., 2019). In projected changes of annual rainfall over southern Africa for the period 2080-2099 compared to present day (1971-2000), the largest rainfall decreases are projected for Angola and the southern parts of South Africa (Archer et al., 2018). The projected decreases in Angola may be occurring in conjunction with changes in the Angola low-pressure system and the strengthening of the subtropical high-pressure belt over southern Africa (Engelbrecht et al., 2009).

Angola is vulnerable to climate change (Brooks et al. 2005). Rainfall over southern Africa is strongly influenced by climate variability in the Angolan Highlands region (Crétat et al. 2019). Synoptic drivers of precipitation in the region, such as the Angola Low, have only recently received strong attention (Howard and Washington 2018). In addition, the drought pattern over southern Africa is not yet fully understood and the role of the Angola Low for moisture transport from the Southern Atlantic remains understudied (Geppert et al., 2022). What is recognised is that the Angolan Highlands have hydrological and ecological importance (McCarthy et al., 2000; Gumbricht et al., 2004; Van Wilgen et al., 2022). Three major transboundary river basins (Congo, Zambezi, and Okavango) are supported by rivers that originate in the study area and the region is the primary source of the Okavango Delta. Climate variability and anthropogenically-induced climate change are likely to have strong implications for water budgets, food security and biodiversity across southern Africa.

Considerable reductions in rainfall projected for southern Angola, in combination with more frequent fires occurring under temperature increases and human-induced land degradation, may result in decreasing tree cover (Engelbrecht et al., 2015; Engelbrecht and Engelbrecht, 2016). This is particularly concerning for communities in the Angolan Highlands region who rely on wood fuel and charcoal production (Taylor et al., 2018). In addition, semi-permanent and permanent smallholder agricultural practices include tree clearing and burning of miombo to generate ash (Schneibel et al., 2017). The main crops that are grown include maize, a variety of beans and cassava (Delgado-Matas et al., 2015; Schneibel et al., 2017; Huntley et al., 2019). The minimum precipitation requirement for agricultural production of these crops ranges from 500 mm (maize) to 700 mm (cassava), although cassava is described as a climate resilient crop and relatively tolerant to low rainfall conditions (Delgado-Matas et al., 2015). In Chapter 6, the lowest rainfall total (888 mm) over the 40-year archive occurred during the 2018/2019 season. Although above the minimum precipitation requirement, this was documented as a period in which at least 1.14 million people were food insecure, and the drought caused severe loss of livestock and low crop yields (RVAA, 2019), highlighting the potential vulnerability of these communities during drought periods. The total precipitation amount does not determine this vulnerability in isolation. Small scale agricultural practices are likely to be more vulnerable to small fluctuations in climate, additional factors including the timing and nature of precipitation are likely to affect this vulnerability.

The miombo woodlands span several countries including Angola, Zambia, Malawi, Zimbabwe, Mozambique, Tanzania, and the DRC (Campbell et al., 2007). These woodlands support the livelihoods of approximately 100 million people and provide

important habitat for wildlife (Campbell et al., 2007; WWF, 2021). The shifting cultivation requires frequent fallowing and clearing of the miombo (Schneibel et al., 2017). It is likely that burn area in the miombo woodlands is underrepresented as satellite fire products used to produce the journal paper presented in Chapter 7 are much less accurate in woodlands and closed canopy systems (Van Wilgen et al., 2022). The region is characterised by increasing land pressure because of continued population growth (Huntley et al., 2019; Schneibel et al., 2017). In a drier and warmer climate, such pressures may hamper adaptive capacity within southern Africa (Archer et al., 2018; IPCC, 2021). Under medium to high mitigation, the region may still experience further climate change, but peak magnitudes of change may be reduced, which have the potential to increase adaptive capacity (Archer et al., 2018; IPCC, 2021). In response to multiple climate-induced challenges, various stakeholders should work collectively to build climate resilience in communities and mitigate against long-term environmental changes on landscapes that are most at risk (Fleming et al., 2021).

8.5 Research Limitations

This is a largely a remote sensing-based study. In recent decades, both the types of satellite remote sensing imagery, and the computational strength to handle big data, have allowed untraversable regions of the world to not only be mapped and classified, but to be quantitatively analysed (Mutanga and Kumar, 2019; Amani et al., 2020). RS applications and platforms can operate independently, but benefit from ground truthing (DeLancey et al., 2019; Mahdianpari et al., 2019). The ground truthing and field work was planned for 2020 and 2021 but were both cancelled due to the COVID-19 pandemic.

The initial ground-based data available this research was several peat cores collected from different locations during previous NGOWP expeditions. Due to the inability to visit the region during the pandemic, steps were taken to produce the first peatland map according to the data obtained from these several verified peatland sites. As RF LULC classifications are reliant on quality ground-truth training data, it was necessary to produce a peatland extent map for the area that was representative of this training data. As a result, the study area, although large, represents a portion (approximately 16%) of the Angolan Highlands region. An advantage of the size of the study region is that coarse spatial resolution RS datasets such as the CHIRPS precipitation and MODIS vegetation and fire were effective in representing the broad scale heterogeneity of the region. However, this study would have benefitted from additional ground truth data.

8.5.1 Data and analytical limitations for each journal paper chapter

In Chapter 4, a wealth of literature concerning peat and peatland definitions were reviewed. However, not all peat and peatland definitions were reviewed as some journal papers had restricted access and were behind paywalls. Most of the definitions used were constrained to available online resources from journal articles, books and reports written in English. In some cases, definitions written in other languages were included, but these originated from texts that had been translated into English. Peat and peatlands occur throughout the world and have global significance, ideally more definitions from different regions and countries would have been included to represent the different perspectives on peatland definitions across the globe.

In Chapter 5, the study relied on background knowledge of LULC data of the Angolan Highlands study site, obtained from previous NGOWP expeditions, to produce the first classification map of potential peatland extent in the region. The study acknowledges that future research would require a complete ground survey to verify the land cover classifications, with particular emphasis on peatland extent. To overcome this limitation, the study provides a conservative estimate of peatland extent obtained from the overlap of two separate LULC RF classifications. The first NGOWP expedition following the pandemic took place in June 2022 after the research was published; this was to verify selected peatland sites used in Chapter 7. This expedition was limited to the peatlands occurring along the Lungui Bungu River and not the entire study region. In addition, high-resolution RS data from Landsat 8 and Sentinel 2 satellites have insufficient spatial resolution to accurately distinguish the small-scale heterogeneity of peatlands (Crichton et al., 2014; Lees et al., 2018). RS data does not provide all the data required (peat depth, bulk density, and carbon content) to estimate the carbon inventory (Lees et al., 2018).

In Chapter 6, precipitation data were obtained from the CHIRPS product as meteorological station data for the region were unavailable. According to the dataset description, CHIRPS combines satellite imagery with in-situ meteorological station data (Funk et al., 2015). As there are no known meteorological station data for the region spanning the period of interest, it is likely that the data is synthesised solely from satellite imagery and does not benefit from accurate ground-based data. The MODIS NDVI and EVI data used in this study are computed from atmospherically corrected bi-directional surface reflectance that have been masked for water, clouds, heavy aerosols, and cloud shadows (Didan, 2015). However, the products contained

data that were contaminated, and these were removed from the time series analysis. Within the time series, where values were removed due to cloud contamination, missing values were replaced by the average of the values on either side of the contaminated period. Therefore, it is likely that some inaccuracy does exist in periods that were more contaminated because of the data-filling methods used.

In Chapter 7, there are no ground-based records of burn area or fire ignitions obtained for the study region, and fire data was obtained solely from the MODIS FireCCI51 product. Furthermore, MODIS fire products have been documented to have some limitations in the detection of wildfires in forested areas, such as the miombo woodlands, due to the closed canopy (Giglio et al., 2006; Beckett et al., 2022). In addition, the study also calculated that the MODIS FireCCI51 fire product had a burn area omission error of 13.82% and 19.30% for 2016 and 2019 respectively, in comparison 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). Although the burn area is comparable and low omission errors occurred in these two years, it is likely that the total burn area for the study is underestimated, especially within the miombo woodlands.

CHAPTER 9: CONCLUSION

9.1 Synthesis

Peatlands have significant ecological, economic, and cultural value (Ramsar, 2002; Limpens et al., 2008) as they provide a range of ecosystem services (Delancey et al., 2019). Peatlands are recognised as a key component of the terrestrial carbon pool (IUCN, 2021), and peatland preservation and health have direct implications on reducing GHG emissions and limiting the impacts of climate change (FAO, 2020). Despite this importance, there is no globally recognised definition for peat or peatland (IPS, 2021), and multiple disparate definitions affect global estimates of peatland extent, volume, and carbon stock (Joosten, 2010). To address this, a critical review on peat definitions was undertaken, this includes a proposed new definition for peatland in the interest of climate science. Mapping peatland extent with accuracy has been documented to facilitate its preservation (FAO, 2020). Peatlands had been identified on exploratory surveys in the Angolan Highlands, a war stricken and under-studied region of ecological and hydrological importance (Conradie et al., 2016; Van Wilgen et al., 2022). The first peatland classification map of the Angolan Highlands was produced using GEE. This included a conservative estimate of peatland extent, the peatland age, and growth dynamics. Peatlands are directly influenced by vegetation and hydrological conditions and are sensitive to drought and fire (Belyea and Malmer, 2004; Page et al., 2011). To address this, the first historical assessment of drought and the vegetation response to drought in the region was produced. In addition, the first assessment of the contemporary fire regimes of the peatlands was produced. The dynamics of these peatlands have direct implications on the environment and communities of the Angolan Highlands and surrounding areas.

9.2 Achievement of study aim and objectives

This PhD has not only advanced our understanding of peat extent, age, and growth dynamics in the Angolan Highlands, but also our understanding of the contemporary drought history and the vegetation response to drought, and the peatland fire regimes. Furthermore, this PhD advances our understanding of the development of peat definitions through time and proposes a new peatland definition for the benefit of peatland science. The primary aim of this research was to investigate dynamics relating to peatland extent, age and growth, and peatland response to drought and fire in the Angolan Highlands. The objectives were developed to address this primary aim through knowledge gaps highlighted in Chapter 1 (Introduction) and three individual research papers (Chapters 5-7). The limitations addressed in the discussion have not compromised the achievement of the study's objectives. The objectives are listed below, as presented in Section 1.3 Chapter 1 (Introduction), along with how these objectives were achieved.

1. To determine and map the extent of peatlands in the Angolan Highlands through machine learning.

This objective required the use of multiple datasets and techniques including RS satellite data, GEE, and AMS radiocarbon dating of peat cores. The outcome of this objective is presented as a journal article in Chapter 5. In this article, the introduction reflects on the importance of peatland mapping, especially within the southern hemisphere and tropics, and peatland deposits in the under-studied Angolan Highlands. The methods section includes details of the study area, the location of peat cores collected by the NGOWP, mapping and analytical techniques and the peat core sampling and AMS dating techniques used. The results include two separate RF

classification maps and the accuracy assessment of each, an overlap map providing a conservative estimate of peatland extent, peatland characteristics with respect to NDVI, NDWI and topographical data, and the radiocarbon chronology including BACON age-depth models of each peat core sample. The discussion includes details regarding the peatland extent in the context of Angola and global peatland inventories, peatland characteristics with respect to vegetation, hydrological and topographical data, and the onset of peat formation, potential carbon storage and peatland threats.

2. To determine the drought history and the vegetation response to drought in the Angolan Highlands region through assessment of historical satellite data products.

The outcome of this objective is presented as a journal article in Chapter 6. The introduction of this article provides the rationale behind the importance of assessing drought history in the Angolan Highlands. The methods section includes details of the study region, the use of RS derived CHIRPS precipitation data due to the lack of meteorological station data for the region, the SPI as a widely used drought index, and the inclusion of MODIS NDVI and EVI vegetation datasets. The results section provides a map of mean precipitation for the region, an assessment of drought frequency according to the 3- ,6- ,12- and 24- month SPI, drought severity and common drought events in relation to ENSO. Included in the results is a map of vegetation greenness, the seasonality of precipitation and separate vegetation regions, and a time series indicating the vegetation response to drought. The discussion includes details of each common drought event in comparison to droughts experienced in surrounding regions and countries. In addition, the discussion highlights the synoptic drivers of drought and includes drought implications and threats of climate change in the region.

3. To determine the contemporary fire regime of peatlands and peatland response to fire in the Angolan Highlands using fire and vegetation satellite data.

This objective draws on the LULC map presented in chapter 5 and includes the use of MODIS fire and vegetation data. The outcome of this objective is presented as a journal article in Chapter 7. The introduction of this article includes details of the importance of the primary LULC classifications (including peatland extent) for the Angolan Highlands. This section also includes the importance of fire in Africa, global emissions and peatland degradation associated with fire, and fire in Angola. The methods section includes a map of the conservative LULC for the region as presented in Chapter 5, the details regarding data acquisition of MODIS fire data and MODIS NDVI data for five separate peatland sites along the Lungui Bungu River. The methods also include details on how fire regimes were calculated for the region, LULC classes and peatland sites. The results include maps of the fire frequency and a timeseries of burn area per year for the study region. Time series of burn area per year for each LULC class and burn proportion per year for each LULC class are included in the results. The results include the average fire frequency for each LULC class, the proportion of each LULC class having specific fire frequencies and the seasonality of fire for each LULC class. Last, a NDVI and burn history time series for each peatland site is included in the results section. The fire patterns across the study area, implications of fire for peatlands, fire management, future research and area conservation are included in the discussion section.

Following the achievements of objectives 2 and 3, the susceptibility of these peatlands in relation to fire and drought can be determined. The active peatlands within the Angolan Highlands have been radiocarbon dated to as having started to accumulate

at least as early as 7100 cal. yr BP, evidently having resistance to both past drought events and fire through time. Since 2001, during periods of extended drought over multiple seasons, the peatland vegetation recovered, responding to the seasonal precipitation occurring within the Angolan Highlands each year. The fire regimes are characteristic of surface fires burning through grassy fuels, and the peatland vegetation recovered within one year of burning, even during drought periods. There is no strong evidence that either drought or fire or a combination of drought and fire, causes peatland degradation within the undisturbed peatlands, indicated by actively growing peatlands at four source lake sites and along the Lungui-Bungu River. However, peatland drainage from human activity is likely to decrease the water table and expose the deep peat soil to aeration and fire, leading to peatland degradation and the release of the stored soil organic carbon. Undisturbed peatlands are resistant to both drought conditions and fire because of waterlogging. Peatland conservation strategies within the Angolan Highlands should focus on preventing water table level reduction. This includes the prevention of peat drainage, extraction, and cultivation.

9.3 Future research directions

Through critical analysis of the peat dynamics in the Angolan Highlands, key research gaps have been identified. These research gaps could lead to future research directions that are discussed in this section. These build on the aims and objectives of this PhD and are based on the individual research paper and general discussion chapters.

The first and possibly most important direction for future research is an investigation of the peatland extent and carbon inventory of the entire Angolan Highlands region

and surrounding basins. As mentioned in chapter 5, the study area comprises only 4.94% of Angola and approximately 16% of the Angolan highlands, it is likely that there may be more tropical peatland deposits (Lawson et al., 2015) to map in the Angolan Highlands and surrounding basins. Future research may also determine whether there is peat forming vegetation within the moist miombo woodlands. Furthermore, as highlighted in Chapter 4, to provide an estimation of the carbon inventory; peatland extent, peat thickness, peat carbon content and peat bulk density (volumetric carbon content) are required in future investigations. Following this quantification, an estimation of whether these peatlands are actively growing or being lost and the potential GHG emissions should be investigated. As mentioned in Chapter 5, the reduction in peat area on both terraces 1 and 2 may imply that the dynamics of peat in the Lungui Bungu River is a net source of atmospheric carbon rather than a sink on geological time, this warrants future further investigation.

Over the last decade, the focus of the literature concerning peat and peatland definitions has steered in the direction of peatland preservation (Finlayson and Milton, 2018; Rieley and Page, 2016; FAO, 2020). As mentioned in Chapter 4, future peatland definitions should focus on carbon storage and potential GHG emissions. A future research direction that would greatly benefit peatland science includes the need for international technical agencies and experts in peatland science to advise and agree on a standard definition for peat and peatland. Furthermore, global peatland maps and inventories should be revised to reflect this standardisation of concepts.

Peatlands provide rich palaeoecological information about changing environments, climate, and land management (Lindsay, 2010). A possible future research direction

could investigate whether important palaeoecological proxies contained in these deposits may be used for climate and environmental reconstruction. As mentioned, climate variability in this region has a strong influence on rainfall over the southern Africa (Crétat et al. 2019). Goyder et al (2018) measured peat to a depth of 5 m; sampling and detailed investigations of deep cores may to reveal changes to the climate system in this important climatic region. Furthermore, collection and AMS radiocarbon dating of additional peat cores would facilitate further investigation of the landscape history, as peatland growth is closely driven by geomorphological processes.

To ensure preservation of this deposit, future investigations and monitoring of important peatland characteristics related to vegetation cover, productivity, water table depth, hydrology, nutrient cycling, and water chemistry are required (Rowland et al., 2021). Additional field-based investigations of the peatland response to drought and fire and human activities will inform and help interpret the mechanisms for peatland formation, growth, and health. An appreciation for the entire Angolan Highlands landscape and ecosystem should be included as the peatlands do not grow in isolation. Furthermore, investigation of the changes to LULC, tree cover, fire, climate, and the environment are necessary in this unprotected region of Angola that is threatened by multiple direct and indirect anthropogenic pressures.

As mentioned in Chapter 6, the observed SPI time series exhibited a decreasing trend, and this could support the notion that drought occurrence and frequency will increase in future. Future research should focus on the adaptive capacity and vulnerability of

communities and landscapes with regards to water shortages experienced in the Angolan Highlands. This should extend to the subsistence agricultural practices and food security of communities at risk. Furthermore, the lack of meteorological station and river discharge data hinder studies related to climate change and river flow dynamics. This should be addressed to provide ongoing monitoring of the freshwater reserves for the region that supports multiple transboundary rivers that flow into several southern African countries. Further research should consider potential adaptive measures for water use, storage, and management in vulnerable communities to mitigate the potential impacts of future drought in the region.

In Chapter 7, the individual LULC classes had slightly differing fire regimes, each requiring further investigation and unique land management practices. Future investigation of the potentially damaging environmental and societal consequences of fire should be addressed. The potential LULC change associated with burn area, burn frequency and seasonality and other contributing factors such as climate change, ground water level change, and human practices should be investigated. In addition, future research could identify whether fire events in the region are as a direct result of human land management practices.

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APPENDIX 1. CHAPTER 4 SUPPLEMENTARY MATERIAL

The supplementary material for Lourenco M, Fitchett JM and Woodborne S (2022) Peat definitions: A critical review. *Progress in Physical Geography: Earth and Environment,* DOI: 10.1177/03091333221118353 is lodged on the journal webpage at https://journals.sagepub.com/doi/suppl/10.1177/03091333221118353/suppl_file/sj-pdf-1-ppg-10.1177_03091333221118353.pdf and replicated below for ease of consultation.

Peat definitions, a critical review

Supplementary Material

Table 1. Definitions, in full, regarding peat nomenclature.

Peat nomenclature (English language) used in definitions.	Definition and reference. (Specific nomenclature used in each definition is bolded).
Peat	In 1930, the Second International Congress of Soil Science defined **peat** as an organic soil at least 50 cm thick, 1 ha in aerial extent and containing < 35% ash (Tie, 1982). "In older soil classification systems, **peat** soils are usually defined as soils having more than 65 percent organic matter" (Andriesse, 1988). "The organic component consists of **peat** deposits containing >17% organic C (>30% organic matter) by weight. Thin as 10 cm but are otherwise greater than 40cm and generally >60cm" (Canadian Agricultural Services Coordinating Committee, 1998: 163). The Soil Survey of England and Wales uses 0.4 m as the minimum depth for a **peat** deposit (Soil Survey of England and Wales cited by Cruickshank and Tomlinson, 1990), whilst 0.5 m is used in Scotland (Soil Survey of Scotland cited by Burton, 1996) and 0.45 m (undrained) in Ireland (Soil Survey of Ireland cited by Cruickshank and Tomlinson, 1990). "**Peat** is sedentarily accumulated material consisting of at least 30% (dry mass) of dead organic material" (Joosten and Clarke, 2002: 24). "**Peat** is defined as having an ash content of 0–55%, muck 55–65%, organic-rich soil/sediment 65–80% and mineral soil/sediment 80–100%. The peat class is further subdivided into very low ash (0–5%), low ash (5–15%), medium ash (15–25%), high ash (25–40%) and very high ash (40–55%) subclasses" (Wüst et al., 2003: 133-134). "**Peat** can be defined as the accumulation of 100% pure organic material which contains at least 65% organic matter or less than 35% mineral content" (Huat et al., 2011: 1988). "The Ministry of Environment of Indonesia defines '**peat**' as a plant residue formed naturally through long-term decomposition processes, accumulating in swamp areas or static reservoirs. The Ministry of Agriculture defines '**peat**' as soil formed as a result of organic matter accumulation with a naturally occurring composition of greater than 65 % from the decaying vegetation growing on it, whose decomposition is slowed down by anaerobic and wet conditions. Meanwhile, the Ministry of Forestry defines '**peat**' as organic matter residue accumulating over a long period of time" (Osaki et al., 2016: 138). "Traditionally, soils with organic carbon content of 12-20% are referred to as organic rich, while above 20% as organic soils (also referred to as **peat**). They satisfied the criteria for Histosol soil type (i.e. **peat**) that requires the presence of a histic horizon (e.g. have at least 12% organic carbon or 20% organic matter if the mineral fraction has no clay) - Of 10 cm thickness or more from the soil surface to a bedrock contact,or - Of 40 cm thickness or more from the soil surface" definition from the Joint Research Centre cited in Panagos et al. (2020: 28-29). "Material that has more organic carbon than in item 2 has been called **peat** or muck. 2. Is saturated with water for 30 days or more (cumulative) in normal years (or is artificially drained) and, excluding live roots, has an organic carbon content (by weight) of: a. Less than 18 percent if the mineral fraction contains 60 percent or more clay; or b. Less than 12 percent if the mineral fraction contains no clay; or c. Less than 12 + (clay percentage multiplied by 0.1) percent if the mineral fraction contains less than 60 percent clay" (US Soil Taxonomy staff, 2014: 3-5).

Peatland	"A **peatland** is an area with or without vegetation with a naturally accumulated peat layer at the surface" (Joosten and Clarke, 2002: 24) and "'**peatlands**' are areas with a minimum peat depth of 30 cm" (Joosten and Clarke, 2002: 42). "**Peatland** is an area with an accumulation of partly decomposed organic matter, with ash content equal to or less than 35 %, peat depth equal to or deeper than 50 cm, and organic carbon content (by weight) of at least 12 %" (Osaki et al., 2016: 145).
True Peat	**True peat** consists of 100 percent organic matter (Andriesse, 1988). **True peat** is defined as organic material of plant origin, excluding coal, with at least 75% organic matter (ASTM, 1969).
True Bog	"A **true bog** is a peat-containing wetland, a major part of whose growing surface receives no inputs from underlying or adjacent mineral soils. Instead, the plants on that part rely on wet and dry inputs from the atmosphere to supply their mineral needs. These plants are said to grow under ombrotrophic conditions (Gk. ombros = rain; Gk. trophe - food); that is, they are fed by the atmosphere" (Davis and Anderson (1991: 4).
Eccentric Bog	"**Eccentric bogs** are true bogs" (Davis and Anderson (1991: 4). "**Eccentric bogs** differ from other bogs in Maine in that they slope mainly in one direction, and they occur on the sides of valleys. The upslope end of the bog abuts or nearly abuts mineral upland. The downslope end borders an unpatterned fen which, in turn, borders a stream or lake in the valley bottom. The bog slope usually has a surface pattern of cross-slope alternating, near-parallel ridges and troughs" (Davis and Anderson, 1991: 6).
Histosol	"**Histosols** (From Gr. histos, tissue; connotative of soils rich in fresh or partly decomposed organic matter): Moor peats (Austral.); Organic soils (Can.); Sols hydromorphes organiques (Fr.); Moorböden (Germ.); **Histosols** (U.S.A.); Bog soils (U.S.S.R.). Eutric Histosols (from Gr. eu, good; eutrophic, fertile). Dystric **Histosols** (from Gr. dys, ill; dystrophic, infertile)" (FAO UNESCO, 1974: 20). "**Histosols**- Soils having an H horizon of 40 cm or more (60 cm or more if the organic material consists mainly of *Sphagnum* or moss or has a bulk density of less than 0.1) either extending down from the surface or taken cumulatively within the upper 80 cm of the soil; the thickness of the H horizon may be less when it rests on rocks or on fragmental material of which the interstices are filled with organic matter" (FAO UNESCO, 1974: 41). "**Histosols** that are saturated with water contain at least 12 or 18 percent organic carbon by weight, depending on the clay content of the mineral fraction and kind of materials. Those that are never saturated with water other than for a few days contain 20 percent or more organic carbon by weight. **Histosols** are well over half organic matter by volume. More than half of the upper 80 cm of a Histosol consists of organic materials unless the depth to rock or to fragmental materials is < 80 cm, a rare condition, or the bulk density is very low" (US Science and Education Administration, 1975: 211). "**Histoso**l - Soils that are predominantly organic, containing at least from 12 to 18% organic carbon, by weight, depending on the clay content of the mineral friction. More commonly called bogs, moors, muskegs, peats or mucks" (Bord na Móna, 1987: xiv). "Traditionally, soils with organic carbon content of 12-20% are referred to as organic rich, while above 20% as organic soils (also referred to as peat). They satisfied the criteria for **Histoso**l soil type (i.e. peat) that requires the presence of a histic horizon (e.g. have at least 12% organic carbon or 20% organic matter if the mineral fraction has no clay) - Of 10 cm thickness or more from the soil surface to a bedrock contact,or - Of 40 cm thickness or more from the soil surface" definition from the Joint Research Centre cited in Panagos et al. (2020: 28-29).
Organic soil	In 1930, the Second International Congress of Soil Science defined peat as an **organic soil** at least 50 cm thick, 1 ha in aerial extent and containing < 35% ash (Tie, 1982). **Soils are organic** if they satisfy requirements 1 and 2, or 1 and 3 from the following list: 1. "Thickness of organic horizon greater than or equal to 10 cm. A horizon of less than 20 cm must have 12 percent or more organic carbon when mixed to a depth of 20 cm. 2. Soils that are never saturated with water for more than a few days must contain more than 20 percent organic carbon by weight (i.e. about 35 percent organic matter). 3. Soils are subject to water saturation episodes and have either: a. at least 12 percent organic carbon by weight (i.e. about 20 percent organic matter) if the soil has no clay;

	or b. at least 18 percent organic carbon by weight (i.e. about 30 percent organic matter) if the soil has 60 percent or more clay; or c. an intermediate proportional amount of organic carbon for intermediate amounts of clay." (FAO, 1998: 45). "Traditionally, soils with organic carbon content of 12-20% are referred to as organic rich, while above 20% as **organic soils** (also referred to as peat). They satisfied the criteria for Histosol soil type (i.e. peat) that requires the presence of a histic horizon (e.g. have at least 12% organic carbon or 20% organic matter if the mineral fraction has no clay) - Of 10 cm thickness or more from the soil surface to a bedrock contact,or - Of 40 cm thickness or more from the soil surface" definition from the Joint Research Centre cited in Panagos et al. (2020: 28-29).
Fen	"Mire is a generic term commonly used to describe all types of peat forming ecosystems, whether swamp, marsh, **fen**, bog, moor or muskeg" (Bord na Móna, 1987: 1) A **fen** is a "peatland which in addition to precipitation water also receives water that has been in contact with mineral soil or bedrock" (Joosten and Clarke, 2002: 166). "A marsh; a **fen**; a bog; a tract of low and watery grounds" (Haslam, 2003: 3).
Mire	"**Mire** is a generic term commonly used to describe all types of peat forming ecosystems, whether swamp, marsh, fen, bog, moor or muskeg" (Bord na Móna, 1987: 1) A **mire** is "a peatland where peat is currently being formed and accumulating" (Joosten and Clarke, 2002: 170) "A **mire** is a wetland that supports a vegetation which is normally peat forming" (Lindsay, 1995: 8). A **mire** is "a piece of wet swampy ground, a boggy place; wet or soft mud, slush, dirt." (Haslam, 2003: 3).
Bog	"Histosols (From Gr. histos, tissue; connotative of soils rich in fresh or partly decomposed organic matter): Moor peats (Austral.); Organic soils (Can.); Sols hydromorphes organiques (Fr.); Moorböden (Germ.); Histosols (U.S.A.); **Bog** soils (U.S.S.R.). Eutric Histosols (from Gr. eu, good; eutrophic, fertile). Dystric Histosols (from Gr. dys, ill; dystrophic, infertile)" (FAO UNESCO, 1974: 20). "Histosol - Soils that are predominantly organic, containing at least from 12 to 18% organic carbon, by weight, depending on the clay content of the mineral friction. More commonly called **bogs**, moors, muskegs, peats or mucks" (Bord na Móna, 1987: xiv). A **bog** is a "mire raised above the surrounding landscape and only fed by precipitation" (Joosten and Clarke, 2002: 163).
Blanket Bog	A **blanket bog** is a "bog which forms a blanket-like layer over the underlying mineral soil" (Joosten and Clarke, 2002: 163).
Raised Bog	A **raised bog** is "usually dome-shaped peatland that has its water level above that of the surrounding mineral soil due to its moisture being fed only by the atmosphere" (Joosten and Clarke, 2002: 173). "**Raised bog** takes the shape of a relative simple dome. The typical **raised bog** occurs in the lowlands and is frequently referred to as lowland raised mire" (Lindsay, 1995: 40).
Quagmire	A **quagmire** is "a shaking marsh; a bog that trembles under the feet" (Haslam, 2003: 3).
Muskeg	"Histosol - Soils that are predominantly organic, containing at least from 12 to 18% organic carbon, by weight, depending on the clay content of the mineral friction. More commonly called bogs, moors, **muskegs**, peats or mucks" (Bord na Móna, 1987: xiv). Mire is a generic term commonly used to describe all types of peat forming ecosystems, whether swamp, marsh, fen, bog, moor or **muskeg** (Bord na Móna, 1987: 1)
Moor	"Histosol - Soils that are predominantly organic, containing at least from 12 to 18% organic carbon, by weight, depending on the clay content of the mineral friction. More commonly called bogs, **moors**, muskegs, peats or mucks" (Bord na Móna, 1987: xiv). A **moor** is "a marsh; a fen; a bog; a tract of low and watery grounds" (Haslam, 2003: 3).

	Moor is the German term indicating "mire" (Joosten and Clarke, 2002: 102).
Morass	A **morass** is "a wet swampy tract, a bog, marsh, occasionally boggy land" (Haslam, 2003: 3).
Mud	"Mire: A piece of wet swampy ground, a boggy place; wet or soft **mud**, slush, dirt." (Haslam, 2003: 3).
Muck	"Histosol - Soils that are predominantly organic, containing at least from 12 to 18% organic carbon, by weight, depending on the clay content of the mineral friction. More commonly called bogs, moors, muskegs, peats or **mucks**" (Bord na Móna, 1987: xiv). "Peat is defined as having an ash content of 0–55%, **muck** 55–65%, organic-rich soil/ sediment 65–80% and mineral soil/sediment 80–100%. The peat class is further subdivided into very low ash (0–5%), low ash (5–15%), medium ash (15–25%), high ash (25–40%) and very high ash (40–55%) subclasses" (Wüst et al., 2003: 133-134). "Material that has more organic carbon than in item 2 has been called peat or **muck**. 2. Is saturated with water for 30 days or more (cumulative) in normal years (or is artificially drained) and, excluding live roots, has an organic carbon content (by weight) of: a. Less than 18 percent if the mineral fraction contains 60 percent or more clay; or b. Less than 12 percent if the mineral fraction contains no clay; or c. Less than 12 + (clay percentage multiplied by 0.1) percent if the mineral fraction contains less than 60 percent clay" (US Soil Taxonomy staff, 2014: 3-5).
Suo	A **suo** is "an area with or without a peat layer dominated by a normally peat-producing vegetation" (Joosten and Clarke, 2002: 175) **Suo** is a Finnish term indicating "mire" (Joosten and Clarke, 2002: 102). "A **suo** is a wetland with or without a peat layer dominated by a vegetation that may produce peat" (Joosten and Clarke, 2002: 24).
Swamp/ swampland	A **swamp/ swampland** is "a tract of low-lying ground in which water collects; a piece of wet spongy ground, a marsh or bog. Originated in North America, land too moist for cultivation, covered by trees and other vegetation, rich soil" (Haslam, 2003: 3).
Marsh/ marshland	A **marsh/ marshland** is "a tract of low-lying land, usually flooded in winter and more or less watery at all times" (Haslam, 2003: 3).
Wetland	A **wetland** is "an area that is inundated or saturated by water at a frequency and duration sufficient to support a prevalence of vegetation typically adapted for life in saturated soil conditions" (Joosten and Clarke, 2002: 177).
Lowland	The typical raised bog occurs in the **lowlands** and is frequently referred to as **lowland** raised mire" (Lindsay, 1995: 40). "In carrying out this assessment, we constrained the data in several ways: firstly, by including only those countries that lie between the Tropics of Cancer and Capricorn (23.5°N and 23.5°S, respectively), which excludes some peatland in the sub-tropics (e.g. Florida Everglades) but includes high altitude peatlands, some of which bear greater resemblance to temperate than **lowland** tropical peatland and, secondly, by defining peat as the surface layer of soil, consisting mostly of partially decomposed vegetation, with an organic content of at least 65% in a minimum thickness of 30 cm" (Page et al., 2011: 5-6).
Everglade	"In carrying out this assessment, we constrained the data in several ways: firstly, by including only those countries that lie between the Tropics of Cancer and Capricorn (23.5°N and 23.5°S, respectively), which excludes some peatland in the sub-tropics (e.g. Florida **Everglades**) but includes high altitude peatlands, some of which bear greater resemblance to temperate than lowland tropical peatland and, secondly, by defining peat as the surface layer of soil, consisting mostly of partially decomposed vegetation, with an organic content of at least 65% in a minimum thickness of 30 cm" (Page et al., 2011: 5-6)
Peat moss/ S*phagnum* moss	"Soils having an H horizon of 40 cm or more (60 cm or more if the organic material consists mainly of ***Sphagnum*** or **moss** or has a bulk density of less than 0.1) either extending down from the surface or taken cumulatively within the upper 80 cm of the soil; the thickness of the H horizon may be less when it rests on rocks or on fragmental material of which the interstices are filled with organic matter" (FAO UNESCO, 1974: 41) "These ecosystems are characterized by the unique ability to accumulate and store dead organic matter from ***Sphagnum*** and many other non-**moss** species, as peat, under conditions of almost permanent water saturation (Joosten and Clarke, 2002: 6).

	"A large number of plant species that occur in mires can contribute to peat formation, such as sedges, grasses, ***Sphagnum*** and other **mosses**, and woody plants. Consequently a wide variety of "botanical" peat types exist" (Joosten and Clarke, 2002: 25). "Slightly humified ***Sphagnum*** peat ("white peat", "peat **moss**")" (Joosten and Clarke, 2002: 56).

Table 2. Definitions and descriptions for each class

Classification term	Definition or description and reference
Ombrogenous and groundwater peat.	"Weber (1902) made the distinction between "ombrogenous" peat and "groundwater" peat, thereby mirroring the concepts of ombrotrophic and minerotrophic" (Lindsay, 2016: 6). "Ombrogenous mires that are fed only by precipitation" (Joosten and Clarke, 2002: 25). "Ombrogenous – water supply stemming solely from precipitation" (Joosten and Clarke, 2002: 29).
Raised Bog	"Weber (1902), who had made a distinction between peatlands fed by mineral groundwater and "raised bogs" which he described as being waterlogged by "meteoric groundwater" (Lindsay, 2016: 3). A raised bog is "usually dome-shaped peatland that has its water level above that of the surrounding mineral soil due to its moisture being fed only by the atmosphere" (Joosten and Clarke, 2002: 173). "Raised bog takes the shape of a relative simple dome. The typical raised bog occurs in the lowlands and is frequently referred to as lowland raised mire" (Lindsay, 1995: 40).
Topogenous and Soligenous	"Groundwater mire systems were subdivided by Von Post and Granlund (1926) into "topogenous" systems that were waterlogged because they lay in topographic basins and "soligenous" systems that were waterlogged by moving water" (Lindsay, 2016: 6). Topogenous mires depend on topographic conditions and are relatively independent of climate, because they develop in terrestrialising lakes or river valleys, or at springs (Von Post 1926). "Topogenous – Originated as a result of the features of an area" (Joosten and Clarke, 176) In soligenous mires, peat formation is not only induced and continued by direct precipitation, but "also by meteoric water running off from the surrounding terrain" (Von Post and Granlund, 1926). "Soligenous – stemming from precipitation water and surficial runoff" (Joosten and Clarke, 2002: 29) "Soligenous – Originating from soil and surface" (Joosten and Clarke, 175).
Geogenous	"Originating from bedrock (e.g. water feeding a mire)" (Joosten and Clarke, 2002: 167). "Geogenous mires that are fed by water which has been in contact with the mineral bedrock or substrate" (Joosten and Clarke, 2002: 25).
Lithogenous	"Lithogenous – stemming from deep groundwater" (Joosten and Clarke, 2002: 29) "Stemming from the lithosphere, as in lithogenous water (deep groundwater)" (Joosten and Clarke, 2002: 169).
Thalassogenous	"Stemming from the sea" (Joosten and Clarke, 2002: 176) "Coastal terrestrialisation mire" (Joosten and Clarke, 2002: 31)
Completely undecomposed peat and completely decomposed peat	Von Post (1924) scale having decomposition ranges from H1–H10, H1: completely undecomposed, H10: completely decomposed. Completely undecomposed peat, releases clear water. Plant remains easily identifiable. No amorphous material (Von Post, 1924) Completely decomposed peat with no discernible plant structure. When squeezed, all the wet peat escapes between the fingers (Von Post, 1924).
Fibric	Mostly Sphagnum, high fibre content (Soil Survey Staff, 1990). Reddish-brown peat with >66% fibres; long slender roots and rootlets with diameters 1-10mm embedded in fibrous or granular matrix from which clear water can be extracted (Esterle, 1990).
Hemic	Mostly reed-sedge, moderate fibre content (Soil Survey Staff, 1990).

	Reddish-brown peat with 33-66% fibres; short or equant fragments of roots or rootlets, bark and leaf fragments generally less than 1cm embedded in the granular matrix from which clear to murky water can be extracted (Esterle, 1990).
Sapric	Low fibre content, often high ash content (Soil Survey Staff, 1990). Dark brown to black fragments, with <33% fibres; fine granular material with the consistency of paste from which water cannot be extruded and deforms as paste upon squeezing (Esterle, 1990).
Oligotrophic	Poor to extremely poor in nutrients (Joosten and Clarke, 2002: 171).
Mesotrophic	Moderately rich in nutrients
Eutrophic	Nutrient-rich (Joosten and Clarke, 2002: 166).
Fen and bog	"Tansley (1939) formally assigned the term "fen" to those peat-forming habitats which ranged from somewhat alkaline to moderately acid conditions as a result of their solute supply and assigned the term "bog" to habitats which were "extremely acid."" (Lindsay, 2016: 3). "The terms "bog" and "mire" were explicitly linked in scientific usage by Tansley (1939) and Godwin (1941) to the presence of a peat soil and with peat-forming conditions." (Lindsay, 2016: 3).
Watershed mire	"This type occurs on watershed plateaux or broad ridges, where the surrounding land slopes away on all sides" (Lindsay, 1995: 48).
Valley side mire	"This type occurs on gently sloping or almost level ground lying between higher, steeper terrain and a watercourse or other water body which forms its lower margin" (Lindsay, 1995: 48).
Spur mire	"Where the shoulder of a hill flattens into a broad spur, this small plateau often carries a patch of blanket bog with a distinctive form" (Lindsay, 1995: 49).
Saddle mire	"This is similar in many respects to the spur mire, but it lies in the depression between two higher slopes and so may receive soligenous influence at each end" (Lindsay, 1995: 49).
Ridge-raised bog	"This form corresponds to the description of the type given by Moore and Bellamy (1974) as two lenses of peat which have fused across an intervening mineral ridge. The profile is similar to that of a raised bog, except with two or more terrestrialised basins between which the peat has subsequently fused" (Lindsay, 1995: 54).
Saddle/ watershed intermediate bog	This type fits within the concept of a semi-confined mire which lies across a saddle or watershed summit and derives much of its shape from the underlying terrain (Lindsay, 1995).
Ombrotrophic and minerotrophic	"Du Rietz (1954) proposed two new formal terms which focused specifically on the source of water supply – namely, "ombrotrophic" for communities fed by rain ("ombros" being Greek for a shower of rain and "trophe" being Greek for food) and "minerotrophic" for communities supplied by the mineral groundwater table" (Lindsay, 2016: 3).
Raised blanket bog	Blanket bog arises through the combination of both paulidifcation and terrestrialisation. The landscape is generally cloaked with peat (Lindsay, 1995)
Tope system	Tope system ranges from Microtope to Nanotope and includes vegetation (Lindsay, 2016). Vegetation – distribution of vegetation within surface structures (smallest level of organisation). Nanotope – individual surface features (e.g., hammock or pool). Microtope – repeated surface features (e.g., pool system). Mesotope sub-sectors – distinction between mire margin and mire expanse. Mosotope morphology – distinct recognisable hydrotopographic unit. Macrotope – assemblage of hydrologically linked mire units (Lindsay, 2016).
Ecological and hydrological mire types	"Succow and Jeschke (1990) made a distinction between "ecological mire types" based on water chemistry and "hydrological mire types" based on hydromorphology"(Lindsay, 2016: 5).
Peat, muck, organic soils (Organic content)	"All soils with organic matter >45% are classified as peat, those with 35–45% as muck and those with 35–20% as organic-rich soils/sediments" (Wüst et al., 2003: 160).
Peat, muck, organic soils (Ash content)	"Peat is defined as having < 55% ash. Peat is further subdivided into five classes: very low ash (0–5%; LOI = 95–100%), low ash (5–15%; LOI = 85–95%), medium ash (15–25%; LOI = 75– 85%), high ash (25–40%; LOI = 60–75%) and very high ash (40–55%; LOI = 45–60%). Organic deposits with 35–45% organic matter and high mineral matter (ash 55–65%) are called muck. These samples have C contents of 12–18%. Organic-rich soils or sediments contain 65–80% ash (LOI = 20–35%) and C contents between 6% and 16%" (Wüst et al., 2003: 159-160)

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APPENDIX 2. CHAPTER 5 SUPPLEMENTARY MATERIAL

The supplementary material for Lourenco M, Fitchett JM and Woodborne S (2022) Angolan highlands peatlands: Extent, age and growth dynamics. *Science of The Total Environment*, 810, 152315. DOI: 10.1016/j.scitotenv.2021.152315 is lodged on the journal webpage at https://ars.els-cdn.com/content/image/1-s2.0-S0048969721073915-mmc1.docx and replicated below for ease of consultation.

Angolan Highlands peatlands: extent, age and growth dynamics.

Supplementary Material

Table 1. Summary table of satellite sensors and bands used in GEE.

Sensor	**Band used**	**Band Description**	**Band resolution (m)**		
Copernicus Global Land Cover Layers	Discrete classification (Buchhorn et al., 2020)	Land cover classification	100		
Sensor	**Bands used in RF classification**	**Band Wavelength (µm)**	**Band resolution (m)**	**Bands used for NDVI with equation**	**Bands used for NDWI with equation**
USGS Landsat 8	Band 2 – Blue	0.452-0.512	30	$\frac{(Band\ 5 - Band\ 4)}{(Band\ 5 + Band\ 4)}$ (Rouse et al., 1974)	$\frac{(Band\ 3 - Band\ 5)}{(Band\ 3 + Band\ 5)}$ (McFeeters, 1996)
	Band 3 – Green	0.533-0.590	30		
	Band 4 – Red	0.636-0.673	30		
	Band 5 – Near Infrared (NIR)	0.851-0.879	30		
	Band 6 – Shortwave Infrared (SWIR) 1	1.566-1.651	30		
	Band 7 – SWIR 2	2.107-2.294	30		
ESA Copernicus Sentinel 2	Band 2 – Blue	0.497	10	$\frac{(Band\ 8 - Band\ 4)}{(Band\ 8 + Band\ 4)}$ (Rouse et al., 1974)	$\frac{(Band\ 3 - Band\ 8)}{(Band\ 3 + Band\ 8)}$ (McFeeters, 1996)
	Band 3 – Green	0.560	10		
	Band 4 – Red	0.665	10		
	Band 5 – Red Edge 1	0.704	20		
	Band 6 – Red Edge 2	0.740	20		
	Band 7 – Red Edge 3	0.783	20		
	Band 8 – NIR	0.835	10		
	Band 8A – Red Edge 4	0.865	20		
	Band 11 – SWIR 1	1.614	20		
	Band 12 – SWIR 2	2.202	20		
Sensor	**Band used**	**Band Description**	**Band resolution (m)**	**Function used to calculate slope**	**Function used to calculate hillshade**
NASA SRTM	Band Elevation	Elevation m. asl	30	ee.Terrain.Slope	ee.Terrain.Hillshade

Table 2. Number and size of land cover training polygons

Land Cover Class	Number of training polygons	Size (km^2)
Peatland	12	0.76
Miombo woodland	10	1.14
Valley grassland	8	1.01
Upland grassland	9	1.51
Water	20	0.91
Cleared/cultivated land	16	0.36
Total	75	5.69

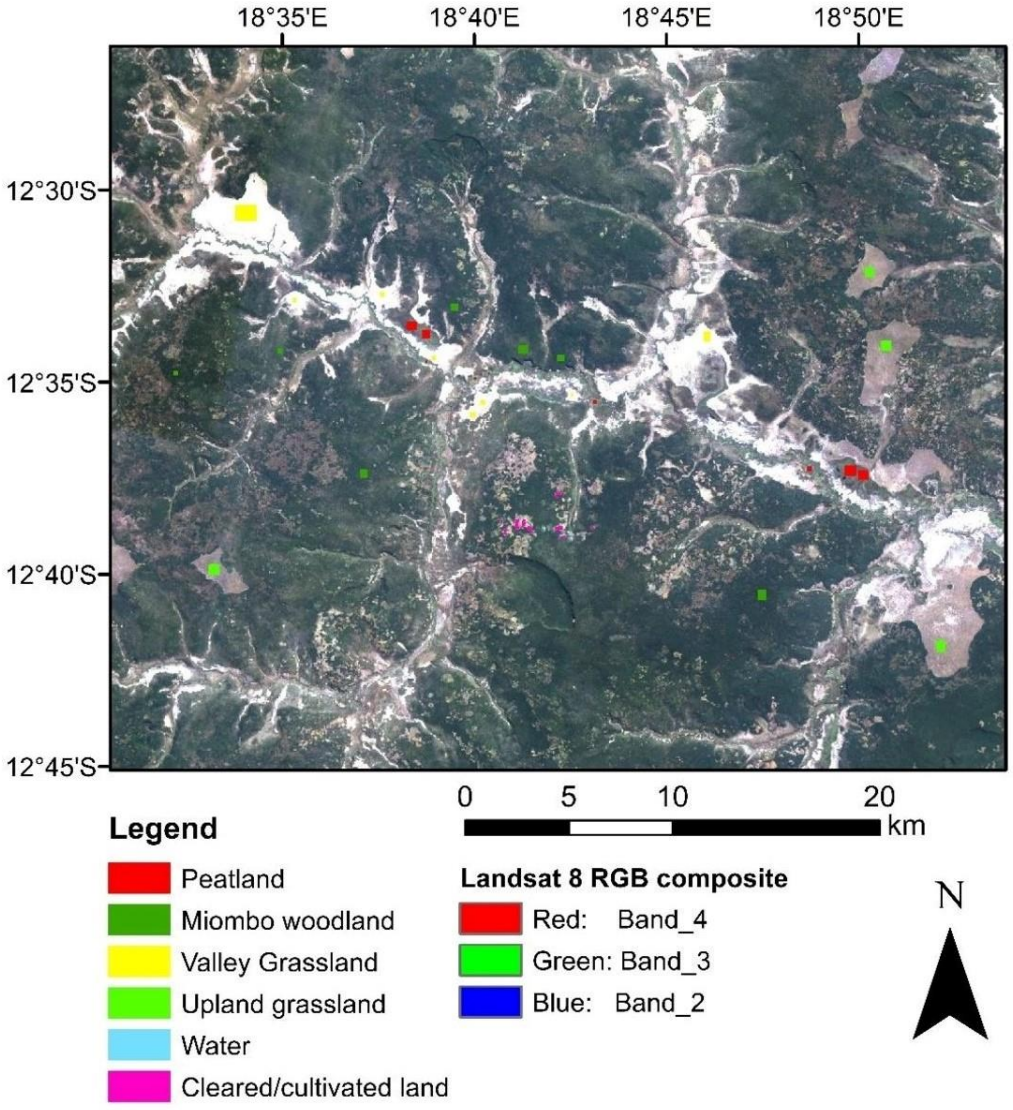

Figure 1. Google Earth Engine training polygons for individual land cover classes.

Table 3. Landsat 8 and Sentinel 2 confusion matrices.

		Reference Data							
	L8 Land cover class	Peatland (pixels)	Miombo woodland (pixels)	Valley grassland (pixels)	Upland grassland (pixels)	Water (pixels)	Cleared/ cultivated land (pixels)	Total Pixels (30m)	Commission Error (%)
Classified data	Peatland	**265**	1	0	1	0	5	272	2,57
	Miombo woodland	0	**390**	0	0	0	1	391	0,26
	Valley grassland	0	0	**362**	0	0	1	363	0,28
	Upland grassland	1	0	0	**502**	0	3	506	0,79
	Water	0	0	0	0	**309**	0	309	0,00
	Cleared/cultivated land	2	0	2	9	0	**99**	112	11,61
	Total pixels (30m)	268	391	364	512	309	109	**1953**	
	Omission Error (%)	1,12	0,26	0,55	1,95	0,00	9,17		

		Reference data							
	S2 Land cover class	Peatland (pixels)	Miombo woodland (pixels)	Valley grassland (pixels)	Upland grassland (pixels)	Water (pixels)	Cleared/ cultivated land (pixels)	Total Pixels (20m)	Commission Error (%)
Classified Data	Peatland	**580**	1	0	4	0	0	585	0,85
	Miombo woodland	4	**873**	0	0	0	0	877	0,46
	Valley grassland	0	0	**787**	0	0	0	787	0,00
	Upland grassland	10	0	0	**1123**	0	7	1140	1,49
	Water	2	0	0	0	**687**	0	689	0,29
	Cleared/cultivated land	0	0	4	24	0	**234**	262	10,69
	Total pixels (20m)	596	874	791	1151	687	241	**4340**	
	Omission Error (%)	2,68	0,11	0,51	2,43	0,00	2,90		

Table 4. Accuracy assessment of the Landsat 8 and Sentinel 2 RF classifications.

Landcover class	Landsat 8				Sentinel 2			
	Pa (%)	Ua (%)	Oa (%)	K	Pa (%)	Ua (%)	Oa (%)	K
Peatland	98.88	97.43	98.67	0.98	97.32	99.15	98.71	0.98
Miombo woodland	99.74	99.74			99.89	99.54		
Valley grassland	99.45	99.72			99.49	100.00		
Upland grassland	98.05	99.21			97.57	98.51		
Water	100.00	100.00			100.00	99.71		
Cleared/cultivated land	90.83	88.39			97.10	89.31		

Pa: producer's accuracy, Ua: user's accuracy, Oa: overall accuracy, and K: kappa coefficient.

Overall accuracy was measured by dividing the total number of correctly labelled samples by the total number of the testing samples. The kappa coefficient indicates the degree of agreement between the ground truth data and the predicted values (Mahdianpari et al., 2019). Producer's accuracy represents the probability that a reference sample is correctly identified in the classification map, and user's accuracy indicates the probability that a classified pixel in the land cover classification map accurately represents that category on the ground (Congalton, 1991).

Table 5. Peatland extent for the study including peatland extent of Angola from various sources.

Region and reference	Total area (km^2)	Peatland Area (km^2)
Angolan Highlands (this study)		
Landsat 8 RF classification	61590	5408
Sentinel-2 RF classification		3690
Overlap map from both classifications		1634
Angola		
Andriesse (1988)	1246700	100
Max for histosols from GDB (2004)		10261
Best estimate from Page et al. (2011)		2640
1990 estimate from Joosten (2010)		10000
2008 estimate from Joosten (2010)		9910

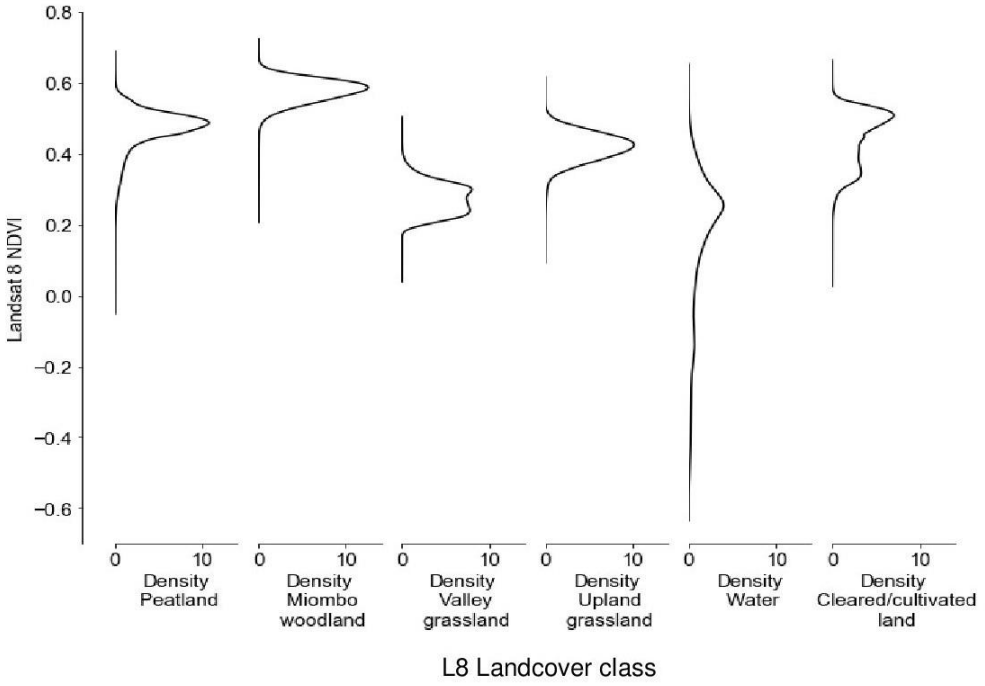

Figure 2. Distribution plots of each L8 landcover class with respect to Landsat 8 NDVI.

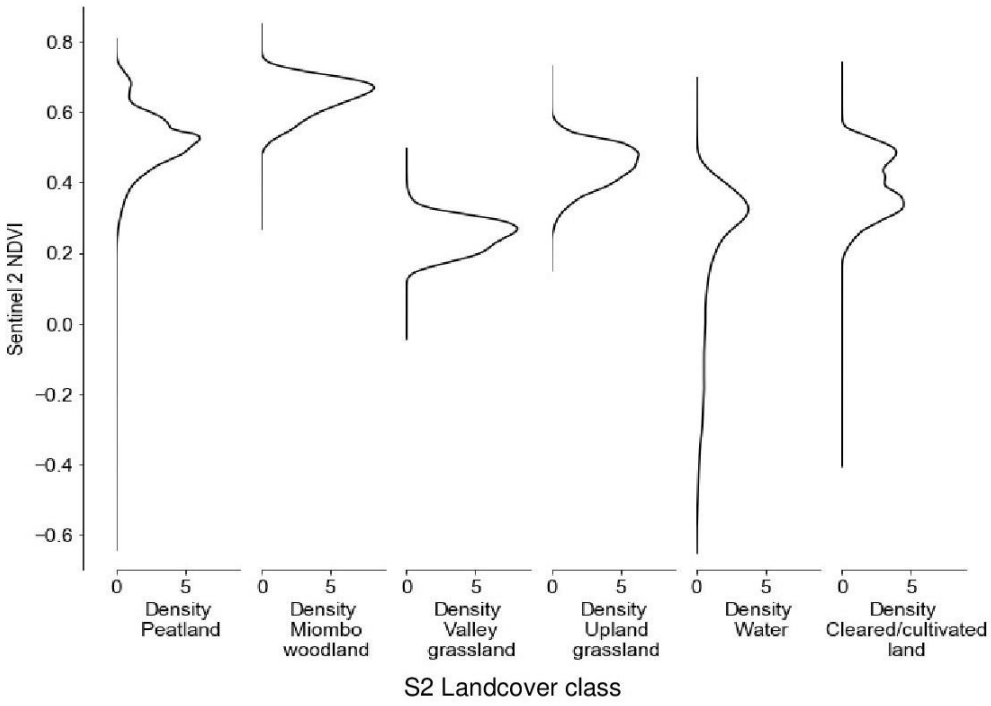

Figure 3. Distribution plots of each S2 landcover class with respect to Sentinel 2 NDVI.

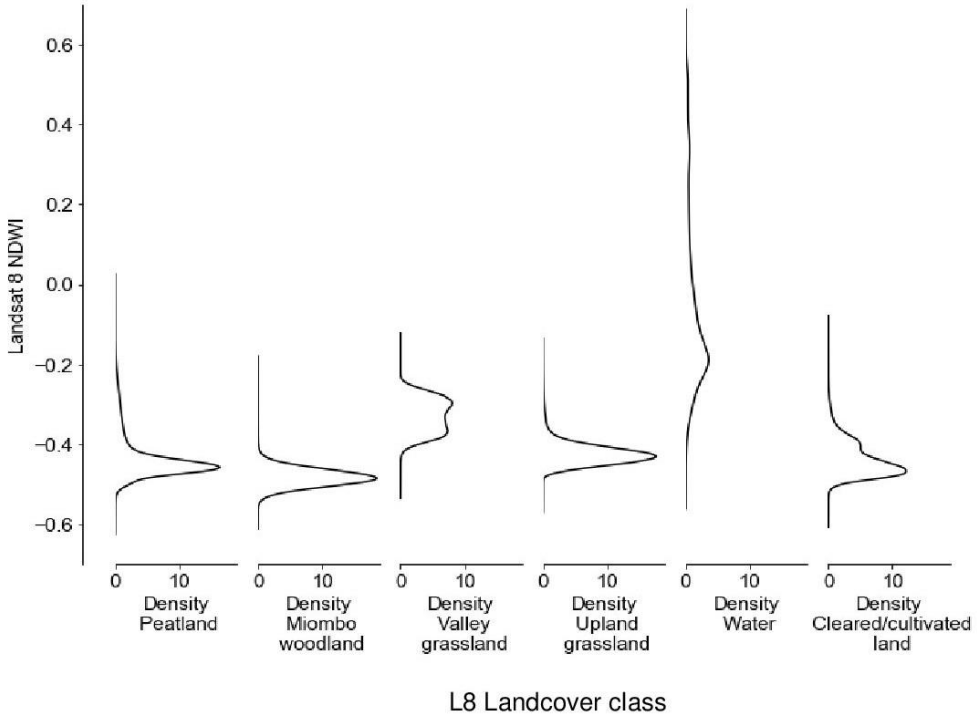

Figure 4. Distribution plots of each L8 landcover class with respect to Landsat 8 NDWI.

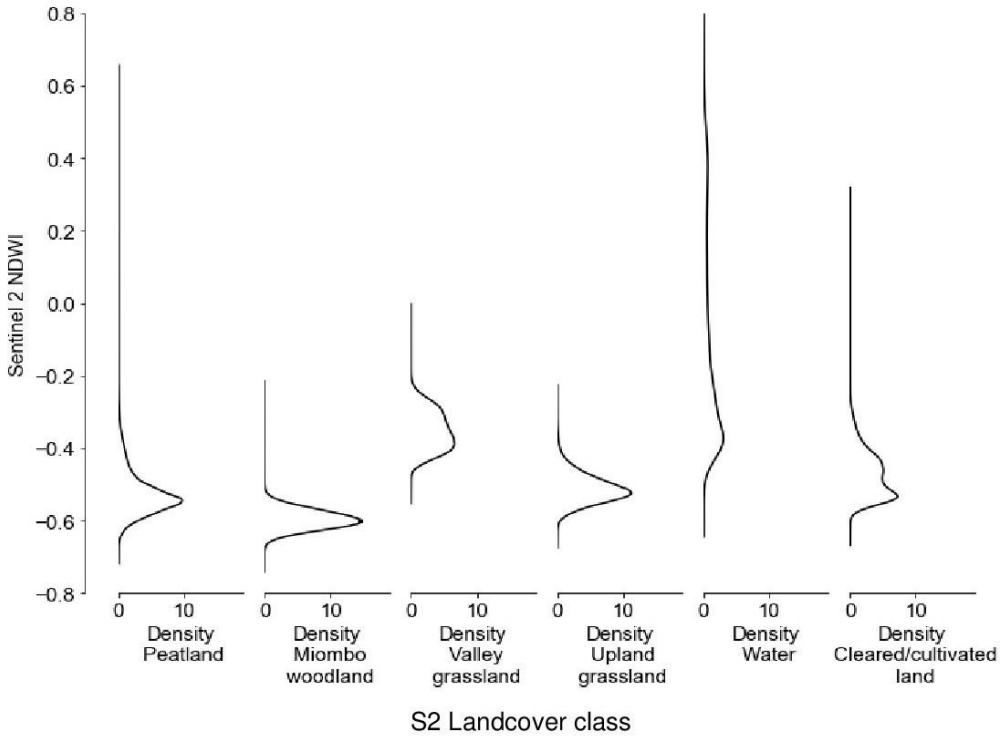

Figure 5. Distribution plots of each land cover class with respect to Sentinel 2 NDWI.

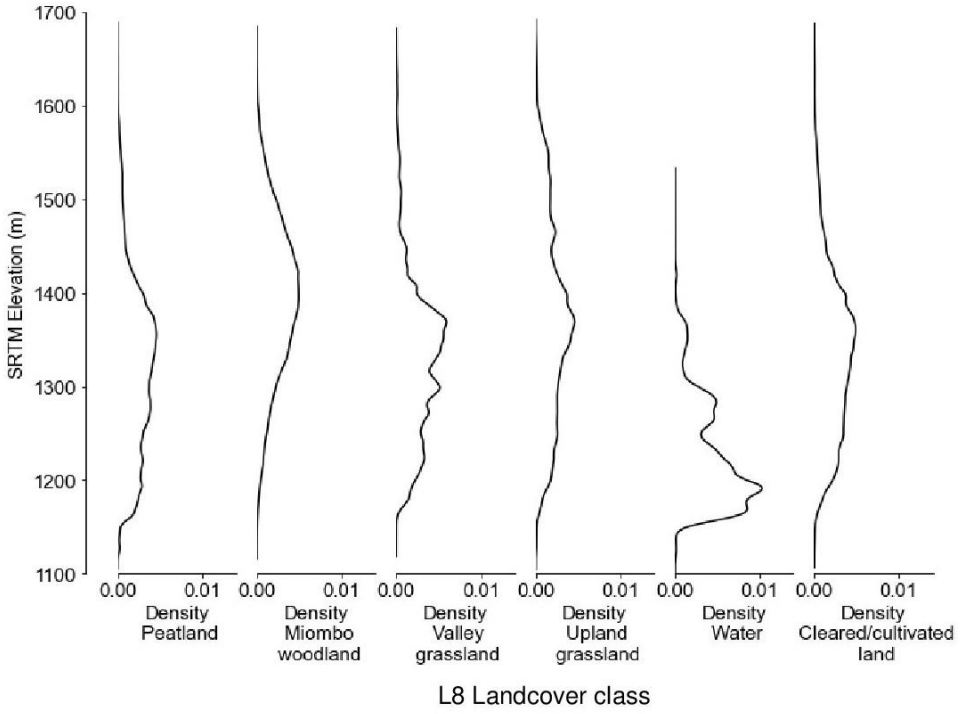

Figure 6. Distribution plots of each land cover class with respect to SRTM Elevation (m).

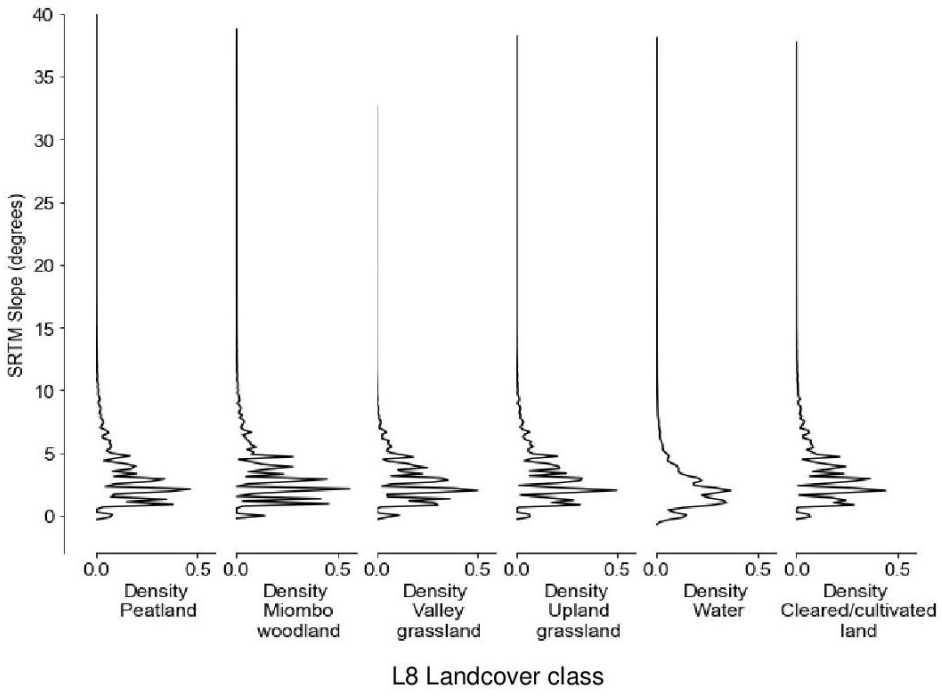

Figure 7. Distribution plots of each land cover class with respect to SRTM Slope

Table 6. AMS ^{14}C dating results for Angolan Highlands peat cores.

Sample	GPS Location	Depth (cm)	$\delta^{13}C$	pMC	pMC err	Age	Age err
Lungui Bungu River (LB) core 1	12°35'2.85"S, 18°39'57.05"E	0-2	-18.0	103.98	0.81	-	-
		50-52	-15.8	89.38	0.45	900	40
		90-92	-25.0	84.32	0.54	1370	52
LB core2	12°34'51.87"S, 18°40'4.78"E	0-1	-17.9	100.28	0.52	-	-
		30-31	-16.8	85.08	0.63	1300	59
		40-41	-25.3	88.63	0.47	970	42
		40-41	-25.3	87.13	0.58	1110	53
LB core 3	12°34'57.67"S, 18°40'1.64"E	0-1	-17.3	109.00	0.57	--690	-
		30-31	-19.8	86.57	0.54	1160	49
		60-61	-24.8	80.81	0.38	1710	38
LB core 4	12°35'11.22"S, 18°39'59.80"E	0-1	-16.0	107.35	0.71	--570	-
		40-41	-18.6	57.98	0.33	4380	46
		70-71	-21.0	46.28	0.41	6190	70
		70-71	-21.0	41.26	0.36	7110	69
Cuando Source Lake (CU)	13° 0'16.04"S, 19° 7'36.70"E	0-1	-16.5	111.06	0.87	-840	
		30-31	-16.0	95.15	0.54	400	45
		59-60	-18.9	87.31	0.45	1090	41
Cuito Source Lake (CS)	12°41'12.42"S, 18°21'46.40"E	0-1	-16.1	107.09	0.46	-	-
		0-1	-17.7	108.44	0.72	-	-
		6-7	-18.8	100.75	0.71	-	-
		12-13	-14.8	97.87	0.35	170	29
		18-19	-17.4	97.56	0.43	200	35
		24-25	-16.5	93.71	0.70	520	60
		30-31	-23.0	92.85	0.65	600	56
		30-31	-13.8	93.07	0.79	580	67
		36-37	-17.8	93.04	0.38	580	32
		42-43	-14.6	92.49	0.39	630	34
		50-51	-21.3	93.34	0.44	550	38
Cuanavale Source Lake (CNV)	13° 5'20.32"S, 18°53'40.36"E	0-1	-20.6	110.81	0.49	-	-
		5-6	-19.3	101.19	0.54	-	-
		9-10	-19.3	100.45	0.67	-	-
		14-15	-18.4	97.93	0.38	170	31
		20-21	-17.9	95.75	0.87	350	72
		30-31	-26.5	88.83	0.52	950	47

δ13C – this is a measurement that indicates the source of the C in the sample and is used in the production of the final date.
pMC – is an acronym for the "percent modern carbon", a standard radiocarbon dating term indicating the sample age. Where pMC values exceed 100 it implies that the peat formed post 1950, and no radiocarbon age is reported
err1 – is the error on the measurement of pMC.
Age – this is the age of the sample expressed in "radiocarbon years" before present (1950).
Err2 is the error estimate on the radiocarbon age.

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APPENDIX 3. CHAPTER 6 SUPPLEMENTARY MATERIAL

The supplementary material for Lourenco M, Woodborne S and Fitchett JM (2022) Drought history and vegetation response in the Angolan Highlands. *Theoretical and Applied Climatology*, DOI: 10.1007/s00704-022-04281-4 is lodged on the journal webpage at https://static-content.springer.com/esm/art%3A10.1007%2Fs00704-022-04281-4/MediaObjects/704_2022_4281_MOESM1_ESM.docx and replicated below for ease of consultation

Drought history and vegetation response in the Angolan Highlands.

Supplementary Material

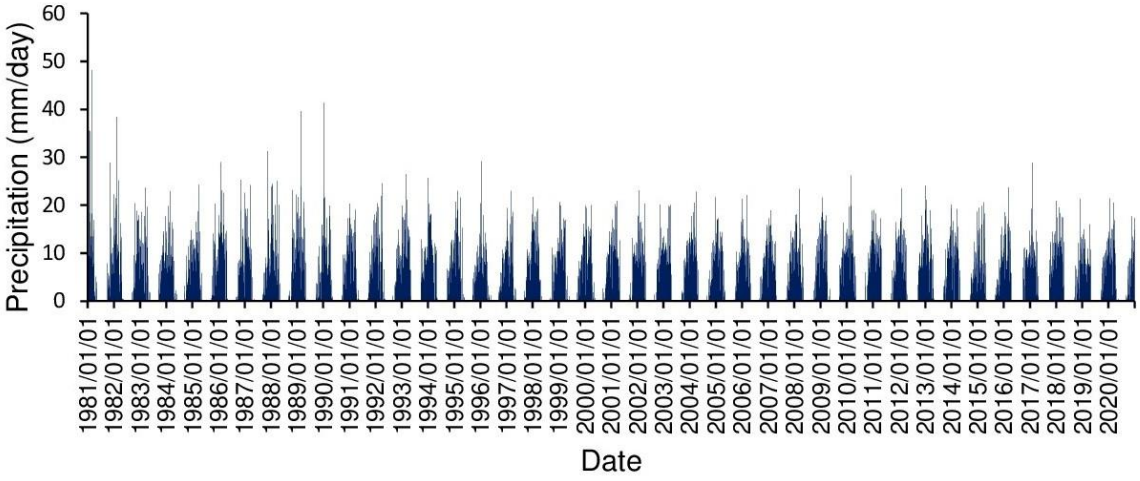

Fig 1 The CHIRPS daily precipitation timeseries record across the Angolan Highlands study area from 1981-01-01 to 2020-12-31.

Table 1. Drought start and end months, peak SPI and drought magnitude for specific SPI timescales.

Drought Start Date	Drought End date	Duration (months)	Peak SPI	Magnitude (cum. SPI scores)	Average SPI
3- month SPI timescale					
1981-06-01	1981-07-01	1	-1.4	-1.4	-1.4
1981-10-01	1982-02-01	4	-1.73	-4.21	-1.05
1982-09-01	1982-10-01	1	-1	-1	-1
1983-02-01	1983-06-01	4	-2.19	-4.57	-1.14
1984-09-01	1984-10-01	1	-1.28	-1.28	-1.28
1986-01-01	1986-02-01	1	-1.81	-1.81	-1.81
1987-05-01	1987-08-01	3	-1.55	-3.33	-1.11
1989-09-01	1990-05-01	8	-3.56	-12.02	-1.5
1990-09-01	1990-10-01	1	-1.13	-1.13	-1.13
1991-06-01	1991-07-01	1	-1.72	-1.72	-1.72
1992-05-01	1992-07-01	2	-1.12	-1.18	-0.59
1994-03-01	1994-07-01	4	-3.08	-7.99	-2
1995-05-01	1995-07-01	2	-1.06	-1.92	-0.96
1995-12-01	1996-07-01	7	-1.74	-7.91	-1.13
1997-02-01	1997-05-01	3	-1.38	-2.04	-0.68
1997-06-01	1997-07-01	1	-1.04	-1.04	-1.04
1998-06-01	1998-07-01	1	-1.38	-1.38	-1.38
1999-11-01	2000-05-01	6	-1.44	-4.72	-0.79
2000-09-01	2001-04-01	7	-1.67	-7.31	-1.04
2001-07-01	2001-08-01	1	-1.31	-1.31	-1.31
2002-07-01	2002-08-01	1	-1.2	-1.2	-1.2
2003-07-01	2004-01-01	6	-1.16	-2.89	-0.48
2004-07-01	2004-08-01	1	-1.31	-1.31	-1.31
2005-09-01	2005-10-01	1	-1.95	-1.95	-1.95
2007-04-01	2007-09-01	5	-1.45	-4.96	-0.99
2008-09-01	2008-12-01	3	-2.29	-4.57	-1.52
2010-10-01	2010-12-01	2	-1.05	-1.21	-0.6
2011-07-01	2011-12-01	5	-1.25	-4.39	-0.88
2012-04-01	2012-09-01	5	-1.73	-5.71	-1.14
2013-05-01	2013-08-01	3	-1.42	-3.78	-1.26
2014-07-01	2014-09-01	2	-1.31	-1.98	-0.99
2014-10-01	2015-06-01	8	-1.96	-9.65	-1.21
2015-10-01	2016-03-01	5	-1.04	-4.02	-0.8
2016-07-01	2016-08-01	1	-1.32	-1.32	-1.32
2017-01-01	2017-10-01	9	-1.29	-8.08	-0.9
2018-10-01	2019-06-01	8	-3.07	-14.52	-1.82
2019-09-01	2019-10-01	1	-1.69	-1.69	-1.69
6-month SPI timescale					
1981-09-01	1982-02-01	5	-1.61	-6.33	-1.27

1983-06-01	1983-09-01	3	-1.61	-2.77	-0.92
1986-01-01	1986-02-01	1	-1.08	-1.08	-1.08
1987-08-01	1987-11-01	3	-1.51	-3.09	-1.03
1989-10-01	1990-06-01	8	-3.56	-15.41	-1.93
1991-09-01	1991-10-01	1	-1.63	-1.63	-1.63
1992-08-01	1992-10-01	2	-1.08	-1.21	-0.61
1994-03-01	1994-11-01	8	-3.08	-14.38	-1.8
1995-08-01	1995-10-01	2	-1.07	-1.94	-0.97
1995-12-01	1997-08-01	20	-1.7	-18.3	-0.92
1997-09-01	1997-10-01	1	-1.15	-1.15	-1.15
1998-09-01	1999-01-01	4	-1.22	-1.88	-0.47
1999-11-01	2000-08-01	9	-1.54	-7.56	-0.84
2000-10-01	2001-05-01	7	-1.96	-7.59	-1.08
2007-07-01	2007-10-01	3	-1.45	-3.19	-1.06
2008-10-01	2008-12-01	2	-1.41	-1.45	-0.72
2011-10-01	2011-12-01	2	-1.34	-1.51	-0.76
2012-06-01	2012-10-01	4	-1.47	-5.39	-1.35
2013-07-01	2013-11-01	4	-1.42	-3.34	-0.84
2014-10-01	2015-09-01	11	-2.11	-14.72	-1.34
2015-10-01	2016-03-01	5	-1.15	-4.86	-0.97
2017-04-01	2017-10-01	6	-1.44	-7.08	-1.18
2018-10-01	2019-09-01	11	-3.33	-22.14	-2.01
12-month SPI timescale					
1981-12-01	1982-02-01	2	-1.23	-2	-1
1983-12-01	1984-02-01	2	-1.25	-1.96	-0.98
1988-02-01	1988-04-01	2	-1.12	-1.77	-0.89
1990-03-01	1990-12-01	9	-1.52	-10.77	-1.2
1994-04-01	1998-01-01	45	-2.4	-54.43	-1.21
2000-02-01	2001-11-01	21	-1.69	-18.31	-0.87
2008-01-01	2009-01-01	12	-1.15	-6.82	-0.57
2015-02-01	2016-03-01	13	-1.95	-21.08	-1.62
2017-03-01	2018-03-01	12	-1.51	-12.32	-1.03
2019-02-01	2020-03-01	13	-2.78	-28.85	-2.22
24- month SPI timescale					
1995-04-01	1999-01-01	45	-2.39	-62.19	-1.38
2001-01-01	2002-10-01	21	-1.75	-15.84	-0.75
2015-03-01	2021-01-01	70	-1,98	-72,92	-1,04

1983-06-01	1983-09-01	3	-1.61	-2.77	-0.92
1986-01-01	1986-02-01	1	-1.08	-1.08	-1.08
1987-08-01	1987-11-01	3	-1.51	-3.09	-1.03
1989-10-01	1990-06-01	8	-3.56	-15.41	-1.93
1991-09-01	1991-10-01	1	-1.63	-1.63	-1.63
1992-08-01	1992-10-01	2	-1.08	-1.21	-0.61
1994-03-01	1994-11-01	8	-3.08	-14.38	-1.8
1995-08-01	1995-10-01	2	-1.07	-1.94	-0.97
1995-12-01	1997-08-01	20	-1.7	-18.3	-0.92
1997-09-01	1997-10-01	1	-1.15	-1.15	-1.15
1998-09-01	1999-01-01	4	-1.22	-1.88	-0.47
1999-11-01	2000-08-01	9	-1.54	-7.56	-0.84
2000-10-01	2001-05-01	7	-1.96	-7.59	-1.08
2007-07-01	2007-10-01	3	-1.45	-3.19	-1.06
2008-10-01	2008-12-01	2	-1.41	-1.45	-0.72
2011-10-01	2011-12-01	2	-1.34	-1.51	-0.76
2012-06-01	2012-10-01	4	-1.47	-5.39	-1.35
2013-07-01	2013-11-01	4	-1.42	-3.34	-0.84
2014-10-01	2015-09-01	11	-2.11	-14.72	-1.34
2015-10-01	2016-03-01	5	-1.15	-4.86	-0.97
2017-04-01	2017-10-01	6	-1.44	-7.08	-1.18
2018-10-01	2019-09-01	11	-3.33	-22.14	-2.01
12-month SPI timescale					
1981-12-01	1982-02-01	2	-1.23	-2	-1
1983-12-01	1984-02-01	2	-1.25	-1.96	-0.98
1988-02-01	1988-04-01	2	-1.12	-1.77	-0.89
1990-03-01	1990-12-01	9	-1.52	-10.77	-1.2
1994-04-01	1998-01-01	45	-2.4	-54.43	-1.21
2000-02-01	2001-11-01	21	-1.69	-18.31	-0.87
2008-01-01	2009-01-01	12	-1.15	-6.82	-0.57
2015-02-01	2016-03-01	13	-1.95	-21.08	-1.62
2017-03-01	2018-03-01	12	-1.51	-12.32	-1.03
2019-02-01	2020-03-01	13	-2.78	-28.85	-2.22
24- month SPI timescale					
1995-04-01	1999-01-01	45	-2.39	-62.19	-1.38
2001-01-01	2002-10-01	21	-1.75	-15.84	-0.75
2015-03-01	2021-01-01	70	-1,98	-72,92	-1,04

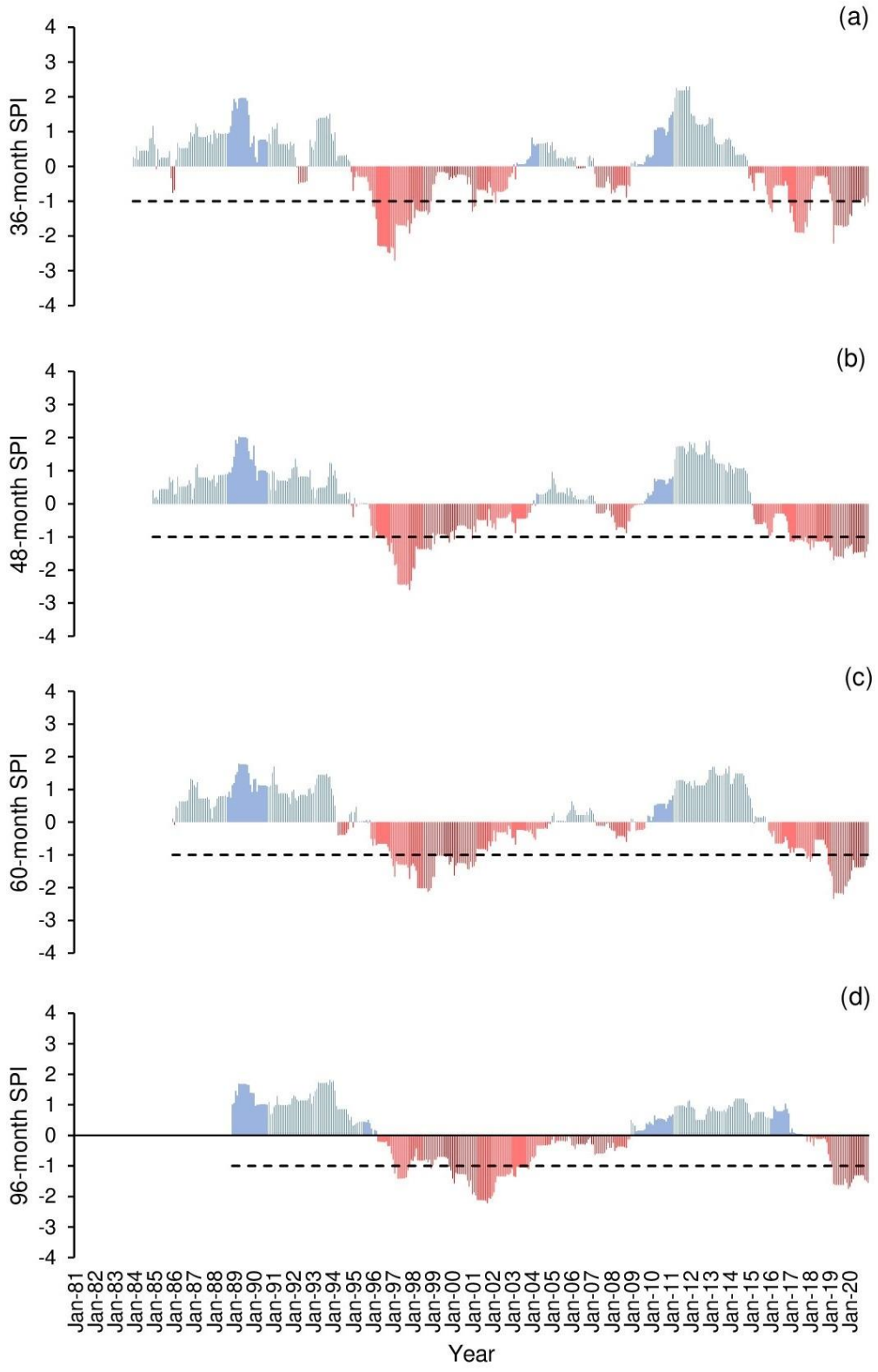

Fig 2 The (a) 36-, (b) 48-, (c) 60- and (d) 96-month SPI plots.

APPENDIX 4. CHAPTER 7 SUPPLEMENTARY MATERIAL

The supplementary material for Lourenco M, Woodborne S and Fitchett JM (2023) Fire regime of peatlands in the Angolan Highlands. *Environmental Monitoring and Assessment*, 195(1): 1–17 DOI: 10.1007/s10661-022-10704-6 is lodged on the journal webpage at https://static-content.springer.com/esm/art%3A10.1007%2Fs10661-022-10704-6/MediaObjects/10661_2022_10704_MOESM1_ESM.docx and replicated below for ease of consultation.

Fire regime and burn frequency of peatlands in the Angolan Highlands

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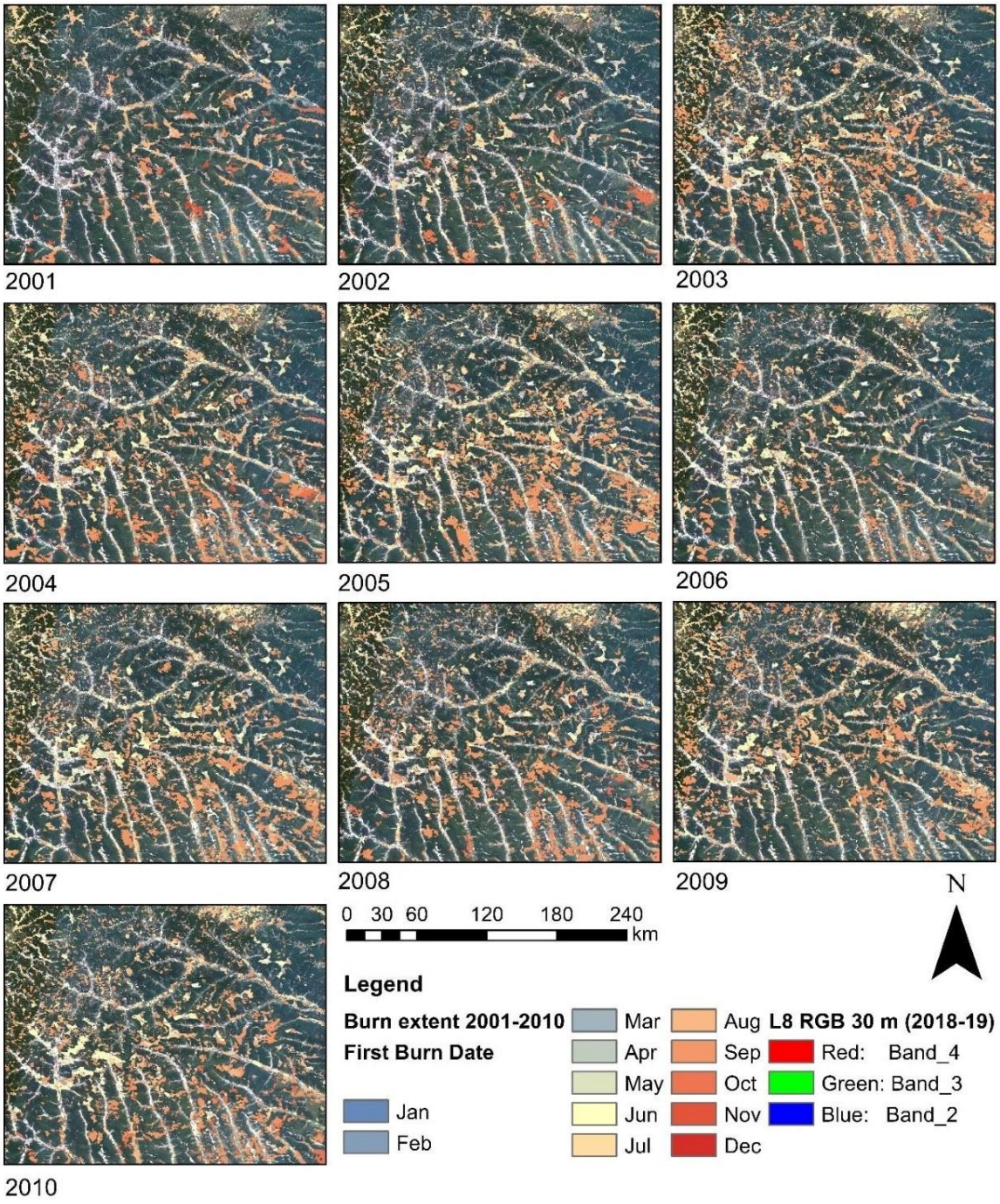
Supplementary Material

Table 1. Summary table of satellite sensors and bands used in GEE.

Fire and Vegetation sensors	Band used	Band Description	Band resolution (m)
MODIS Fire_cci Burned Area pixel product version 5.1 (Chuvieco et al., 2018a)	Burn date	Estimated day of the year of the first detection of the burn	250
MODIS MOD13Q1.006 Terra Vegetation Indices (Didan, 2015)	NDVI	Normalised Difference Vegetation Index	250


2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
0 30 60 120 180 240
km
N
Legend
Burn extent 2001-2010
First Burn Date
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
L8 RGB 30 m (2018-19)
Red: Band_4
Green: Band_3
Blue: Band_2

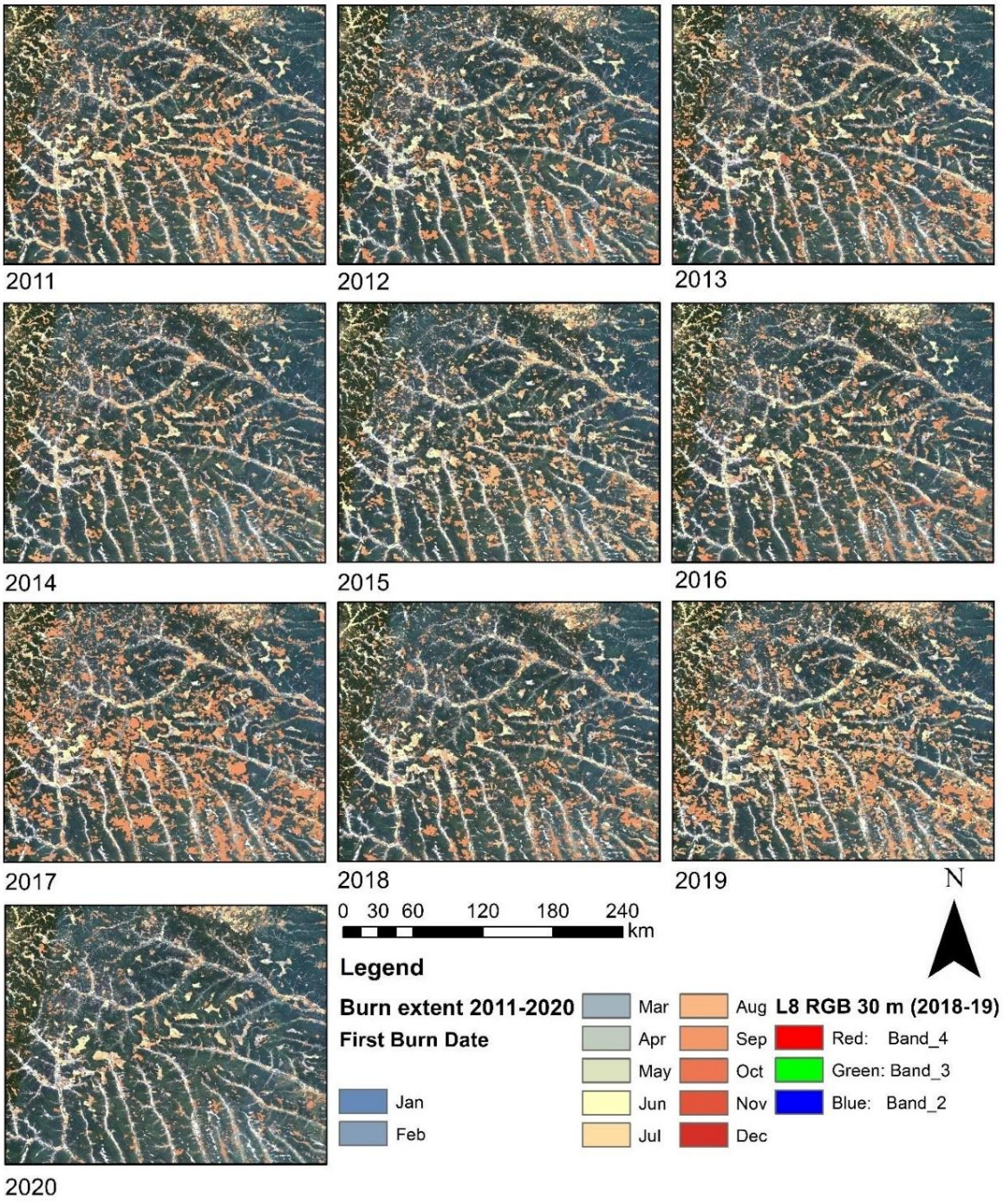


Fig. 1 Background Landsat 8 satellite (RGB) image of the Angolan Highlands study area including an overlayed layer indicating burn pixels and date of first burn (burn month indicated in the colour palette ranging from blue to orange to red) for each year from 2001 to 2020.

Total burn during 2016 according to the MODIS FireCCI51 product =10853.69 km^2, total for the SFD Fire_cci v1.1 product = 12593.56 km^2. Burn area omission error = 13.82% for 2016 (Fig. 2).

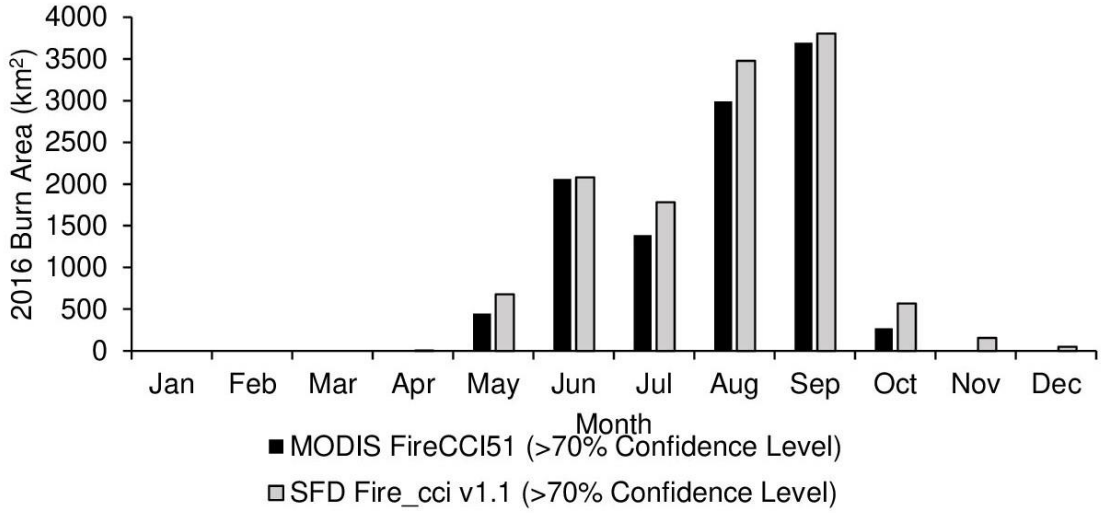


Fig. 2 Burn Area per month during 2016 for the MODIS FireCCI51 and SFD Fire_cci v1.1 product (Roteta et al., 2019), confidence level >70% for both products.

Total burn during 2019 according to the MODIS FireCCI51 product =16888.81 km^2, total for the SFD Fire_cci v1.1 product = 20928.21 km^2. Burn area omission error = 19.30% for 2019 (Fig. 3).

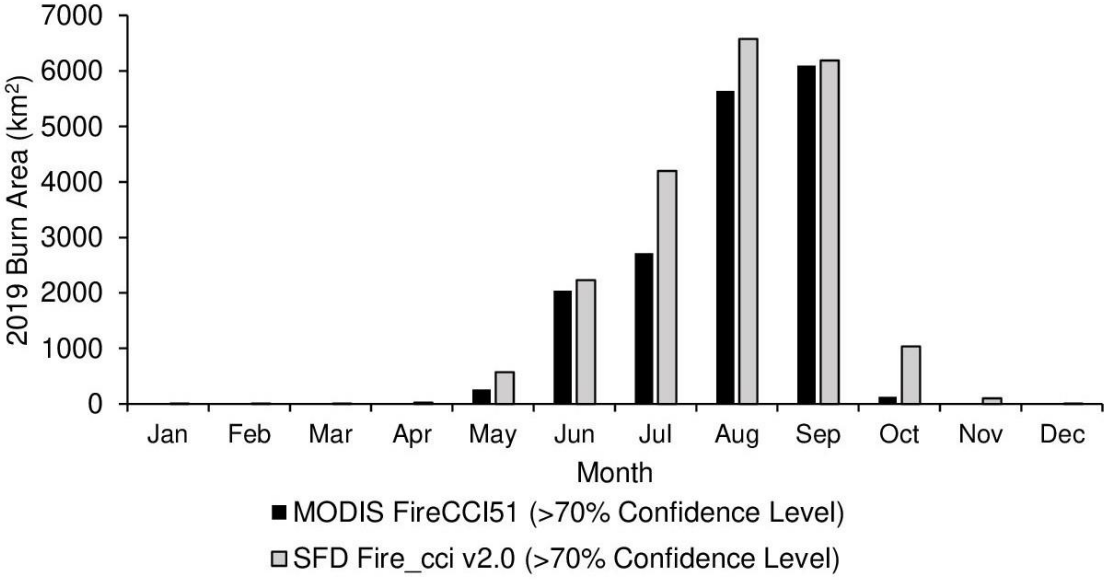


Fig. 3 Burn Area per month during 2019 for the MODIS FireCCI51 and SFD Fire_cci v1.1 product (Chuvieco et al., 2022), confidence level >70% for both products.

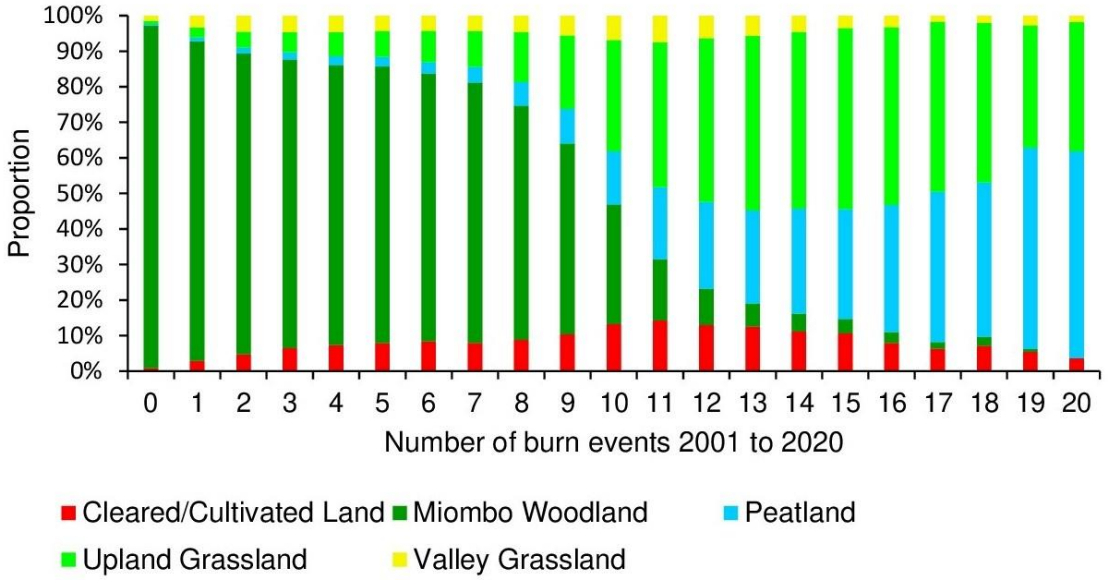


Fig. 4 Proportion of area which burned between 0 to 20 times for each class from 2001 to 2020

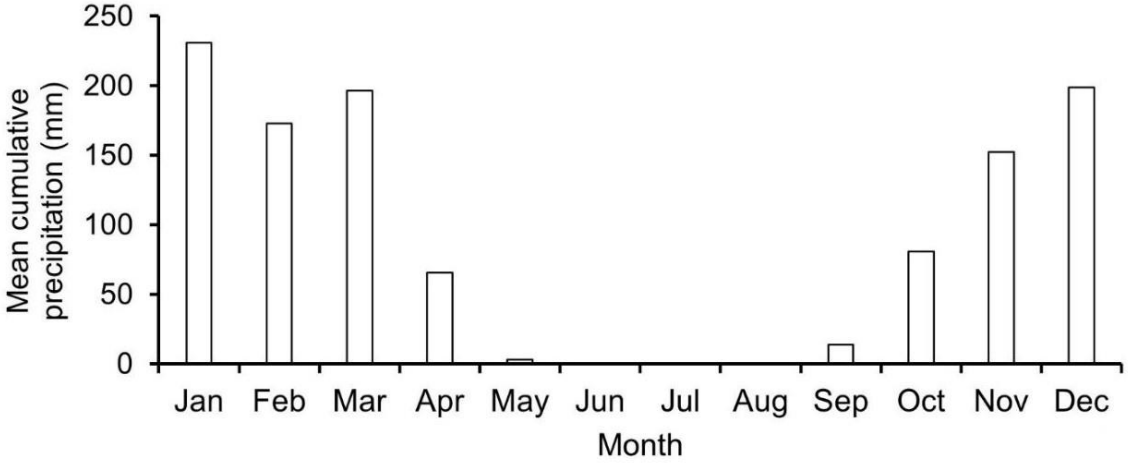


Fig. 5. Average monthly cumulative precipitation in the Angolan Highlands study region (1981-2020).

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