Spatial and Temporal Trends of Burnt Area in Angola: Implications for Natural Vegetation and Protected Area Management

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Abstract: Fire is a key driver of natural ecosystems in Africa. However, human activity and climate change have altered fire frequency and severity, with negative consequences for biodiversity conservation. Angola ranks among the countries with the highest fire activity in sub-Saharan Africa. In this study, we investigated the spatial and temporal trends of the annual burnt area in Angola, from 2001 to 2019, and their association with terrestrial ecoregions, land cover, and protected areas. Based on satellite imagery, we analyzed the presence of significant trends in burnt area, applying the contextual Mann–Kendall test and the Theil–Sen slope estimator. Data on burnt areas were obtained from the moderate-resolution imaging spectroradiometer (MODIS) burnt area product and the analyses were processed in TerrSet. Our results showed that ca. 30% of the country's area burned every year. The highest percentage of annual burnt area was found in northeast and southeast Angola, which showed large clusters of decreasing trends of burnt area. The clusters of increasing trends were found mainly in central Angola, associated with savannas and grasslands of Angolan Miombo woodlands. The protected areas of Cameia, Luengue-Luiana, and Mavinga exhibited large areas of decreasing trends of burnt area. Conversely, 23% of the Bicuar National Park was included in clusters of increasing trends. Distinct patterns of land cover were found in areas of significant trends, where the clusters of increasing trends showed a higher fraction of forest cover (80%) than the clusters of decreasing trends (55%). The documentation of burnt area trends was very important in tropical regions, since it helped define conservation priorities and management strategies, allowing more effective management of forests and fires in countries with few human and financial resources.

Keywords: wildfires; MODIS burnt area product; WWF ecoregions; land cover; Miombo woodlands; biodiversity conservation; sub-Saharan Africa

1. Introduction

Fire is considered a key driver of biodiversity [1], playing an important role in the structure and distribution of ecosystems and biochemical cycles [2]. It determines the distribution, ecology, and maintenance of African savannas and grasslands [3–5]. Over the last million years, the frequent

occurrence of fires in Africa promoted the evolution of a more fire-tolerant and dependent flora [6]; without fire, large areas of savannas could develop into closed woodlands [4].

In southern Africa, however, the severity of fires caused by human activity is increasing [7], with negative consequences for biodiversity conservation and climate change. Approximately 70% of the global burnt area and 50% of fire-related carbon emissions are produced in Africa [8,9]. Uncontrolled fires can greatly damage residential zones, agricultural areas, and forests that are not adapted to fire, contributing to deforestation in many African countries, and producing gas emissions with harmful effects on human health and global climate [10–12]. In Africa, wildfires were identified as the main driver of forest degradation in remote areas of forests, which are more likely affected by recurring fires than by timber extraction [13]. On the other hand, fires are also used in the traditional slash-and-burn agriculture, which consists of cutting trees and woody plants from an area and then burning biomass, resulting in nutrient-rich ash that makes the soil more fertile for agriculture and grazing [13,14]. Savanna fires start by natural causes, mainly lightning, and human intervention, but the relative share of anthropogenic fires is quickly increasing in Africa. In savannas of West Africa, human activity is the most important factor causing fires [11].

The size of burnt areas varies greatly across countries and depends on rainfall seasonality, human activity, and available fuel [15,16]. The fire regime is strongly related to the land use practices and rural populations greatly influence the extent of fires and the annual area burnt [16,17].

Historically, humans have used fire to clean the land [16]. The rural population, which continues to grow in many African countries, frequently uses fire to promote grass growth for cattle to eliminate agricultural residues after harvests and to clear agricultural lands [16]. Moreover, wood and charcoal are the main sources of energy for cooking and heating in rural communities, their use enhancing the exploitation of natural resources and deforestation [11]. An increase in biomass burning causes local drying of the atmosphere, reducing rainfall in the region [12].

According to Archibald et al. [18], Angola, Zambia, and Mozambique are the countries with the most fire activity in southern Africa. In these countries, where the fires are mainly grass-fueled surface and closely related with areas of grass vegetation, such as savannas, grassland, forest and transitions, approximately 50% of the land area was affected by fire between 2001 and 2008, and a large part of it was burnt more than four times during this period [18].

Angola encompasses a great diversity of habitats from desert to tropical rain forests but is dominated by grasslands, savannas, and scrublands [19]. In total, 15 different ecoregions of the global ecoregions map of World Wildlife Fund (WWF) are present in Angola [20], of which the most widespread are the Miombo woodlands of the central plateau, and the western Congolian forest-savanna mosaics in the north [21]. Other important but less extensive ecoregions found in this country are the Atlantic Equatorial coastal forests in Cabinda and the mopane woodlands and the Namibian savanna woodlands in the southwest [20]. In this country, fires are generally classified as surface fires, occurring mainly during the dry season between late April and November [22,23]. Northern regions and central highlands burn considerably earlier than southern zones, when the grass fuel contains higher moisture, resulting in cooler, less intense fires that are less damaging to vegetation than the later and hotter fires in southern Angola [15,23].

Over the last years, intense fires are becoming more frequent in Angola [23]. Very dry seasons and consecutive years of drought with low-humidity conditions promote an increase in the occurrence and intensity of fire [24]. Moreover, droughts have led to significant food insecurity, reducing many populations to subsistence conditions and increasing use of fire to clear hunting zones and preparing new ones for cultivation [14]. Recent studies [23,25] show that Angolan forests have been strongly affected by severe and recurrent fires. Although a single fire has no strong effect on tree composition, the damage caused by recurrent fires in the late dry season can cause high tree mortality [26]. For woodlands in south Africa, a period of at least 5 years without fire is necessary for the successful reestablishment of some tree species [27,28], but such an interval rarely happens in Angolan savannas [17,29].

Currently, deforestation continues to increase in Angola, where one of the highest rates of tree cover loss in sub-Saharan Africa occurs [30–32]. Most of the native trees are under severe pressure due to logging, wood harvesting and charcoal production [21,33,34], as well as fire-related human and climate factors [35–37]. With southern Angola expected to become drier and warmer as a consequence of climate changes, fire frequency is likely to increase and the conservation of Angolan forests and savannas is urgently needed [38,39]. Effective biodiversity conservation requires that fire plays a natural role in ecosystems without representing a threat to ecosystems or human well-being [40].

The current forest degradation caused by fires is difficult to quantify, requiring a comparison of repeated measurements over time [26]. Over the last two decades, remote sensing has become a very useful technique to map burnt areas at regional and global scales, providing a comprehensive view of landscape patterns of fire (e.g., [10,18,29,41,42]). Mapping burnt areas over the years is crucial for resource managers to understand fire impacts on habitats, wildlife, and human settlements, particularly in the context of global climate change [11]. The moderate-resolution imaging spectroradiometer (MODIS) has been extensively used for the study of fire and burnt areas, including in southern Africa [18,24,25]. For instance, Archibald et al. [18] analyzed fire regimes in southern Africa, based on fire frequency, fire seasonality, fire radiative power, and fire size, as well as their relationship to human activities. Mishra et al. [24] examined how variations in burned area and fire frequency were determined by rainfall, vegetation morphology, and land use in the semiarid savanna of Botswana. Schneibel et al. [25] studied the role of fire in forest degradation processes in south-central Angola. However, the study of spatial and temporal trends of burnt area and the determination of its magnitude have never been carried out in Angola. MODIS derived burnt-area product (MCD64A1) is based on changes in surface reflectance over time and includes per-pixel burnt area and quality information about recent fires [43,44]. It is available as monthly global maps, with good detection of small burns, low temporal uncertainty, and a small extent of unmapped areas [18,44,45].

The main goal of this study is to analyze spatial and temporal trends of the area annually burnt in Angola between 2001 and 2019, and how these trends affected the conservation goals of the country, i.e., the sustainable use of natural resources, the recovery of its biodiversity, and the rehabilitation of its protected areas after almost 30 year of war [14]. Specifically, we aimed to: (i) map fire incidence in Angola between 2001 and 2019; (ii) detect and analyze positive and negative trends in the annual burnt area; and (iii) analyze the association between the detected trends and the Angolan ecoregions, protected areas, and land cover classes. Our results will provide new data and useful information for the sustainable fire management and conservation of Angolan ecosystems.

2. Materials and Methods

2.1. Study Area

With ca. 1,246,700 km^2, the Republic of Angola is the largest country in southern Africa. It is located between 4°22′ S and 18°02′ S, and 11°41′ E and 24°05′ E, and is organized into 18 provinces (Figure 1). The mean annual rainfall varies between ca. 50 mm in Namib and more than 1500 mm in Lunda Norte [46]. A very diverse climate and topography originated high species richness and habitat heterogeneity. In total, 15 ecoregions are recognized in Angola [20] (Figure S1), including deserts, savannas, grasslands, tropical forests, and mangroves. The current system of protected areas includes 14 areas (Figure 1), covering about 13% of the country [47,48].

With a population of over 26 million people and an annual growth rate of 3.3% according to the 2014 population census [49], this country struggles with food scarcity, poor medical support, and lack of infrastructures [25]. Approximately 37% of the population lives in rural areas and depends on agriculture for food and financial income [49,50]. The expansion of agricultural and urban areas and the demand for agricultural land are important causes of anthropogenic fire and deforestation [34,51].
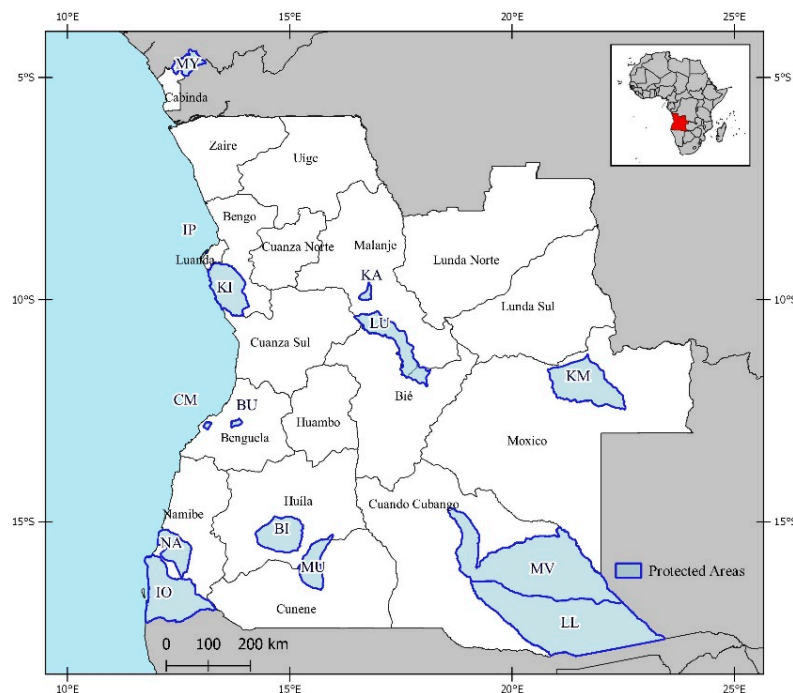
Figure 1. Study area, with the 18 provinces of Angola and the protected areas system: BI, Bicuar; BU, Búfalo; KA, Cangandala; CM, Chimalavera; IO, Iona; IP, Ilheu dos Pássaros; KM, Cameia; KI, Quiçama; LL, Luengue-Luiana; LU, Luando; MV, Mavinga; MU, Mupa; MY, Maiombe; NA, Namibe.

2.2. Burnt Area Data, Trend Estimation, and Testing

Data on burnt areas in Angola were obtained from the MODIS burnt area product MCD64A1 v.006 [52] and downloaded using the Google Earth Engine platform. These data are produced from MODIS Terra and Aqua daily surface reflectance products at 500 m resolution [52–54]. Based on the daily surface reflectance, the algorithm identifies rapid changes to detect burning events and maps their spatial extent [52,54]. The algorithm uses a burn sensitive vegetation index derived from MODIS shortwave infrared atmospherically corrected surface reflectance to create thresholds that are applied to composite imagery data and then spatial and temporal active-fire information is used to estimate probabilistic thresholds suitable to classify individual grid cells as burnt or unburnt [44,52].

MODIS Terra and Aqua satellites were launched at different times. While the Terra sensor has been collecting data since February 2000, the Aqua sensor has been collecting data since June 2002 [55]. As the post-fire signal is persistent and the product of the burnt area is not very sensitive to the time of satellite passage [56], losing little information with just one sensor, we used monthly data from January 2001 to December 2019.

To analyze the mean annual fraction of the burnt area and the number of years of burning, we summed the data for the 12 months of each year (January to December) and resizes the resulting maps to a 5 km resolution grid using QGIS v.3.4.4 software [57]. Each cell was reclassified with the percentage of area burned and the number of years in which it was burned.

The analysis of the spatial and temporal trends of the burnt area was processed in TerrSet v.18.31 [58]. To avoid sequential correlation in time series (i.e., the lack of independence between observations), we applied the Durbin-Watson serial correlation test [59–61] and the pre-whitening procedure proposed by Wang and Swail [62], which maintains the same trend as the original series, but without serial correlation.

To identify significant trends, we applied the Mann–Kendall test [63,64] and the contextual Mann–Kendall test [65]. The Mann–Kendall test is a nonparametric test of trend monotonicity and a common approach in studies of environmental time series [61,65,66]. The contextual Mann–Kendall test, proposed by Neeti and Eastman [65], is a modified version of the Mann–Kendall test that includes

geographical contextual information, i.e., neighboring cells are involved in the determination of trends, allowing the detection of homogeneous regions with similar trends. The contextual analysis imparts greater confidence to the identified trends [61].

Then, the Theil–Sen slope estimator was applied to determine the rate of burnt area change in each cell with significant trends [67,68]. This non-parametric technique is robust against outliers and provides an indicator of change over time [66]. It is defined as the median of the slopes calculated between observations in all pair-wise time steps and is suitable for application to time series with large annual variations, such as those concerning annual burnt area [61]. An increasing trend is indicated by a positive Z value, while a decreasing one is indicated by a negative Z value.

2.3. WWF Ecoregions, Protected Areas, and Land Cover Data

Ecological conditions, changes in land use, and population dynamics are important drivers of fire occurrence over time. To analyze the association between these factors and the trends of the burnt areas, we compared the maps of burnt area trends with the WWF ecoregions (Figure 2a) [20], the Angolan system of protected areas [47], and land cover time-series maps (Figure 2b) [69,70].

WWF terrestrial ecoregions represent the high variability of biogeographic diversity and ecological conditions (see Figure 2a) [20,71–73]. This map was produced at a global scale and reflects the regionalization of the Earth's terrestrial biodiversity, defining units that contain a distinct assemblage of natural communities sharing a large majority of species, dynamics, and environmental conditions [20]. WWF ecoregions has been used as a basis for studies on biotic diversity and conservation in Angola [19,21,74].

Maps concerning the Angolan system of protected areas were downloaded from the World Database of Protected Areas [75]. The present extent of Luengue-Luiana and Mavinga national parks was not updated in WDPA, so it was vectorized based on published Angolan legislation (Diário da República de Angola, law 38/11 29 December 2011, p. 6340).

Land cover data were obtained from the European Space Agency (ESA) Climate Change Initiative Land Cover (CCI-LC) project [76] which produced annual land cover maps for 1992–2015 (version 2.0.7) and 2016–2018 (version 2.1.1), combining remote sensing products and ground observations [69,70]. These maps provide data describing the land surface at 300 m resolution, divided into 22 classes (see Figure 2b). To understand changes in land cover over time, we used the most recent land cover data available (2018) and data collected every four years (2002, 2006, 2010, and 2014). Finally, the maps of burnt area and significant trends were spatially intersected with the WWF ecoregions, protected areas, and land cover maps using QGIS v.3.4.4 software [57].
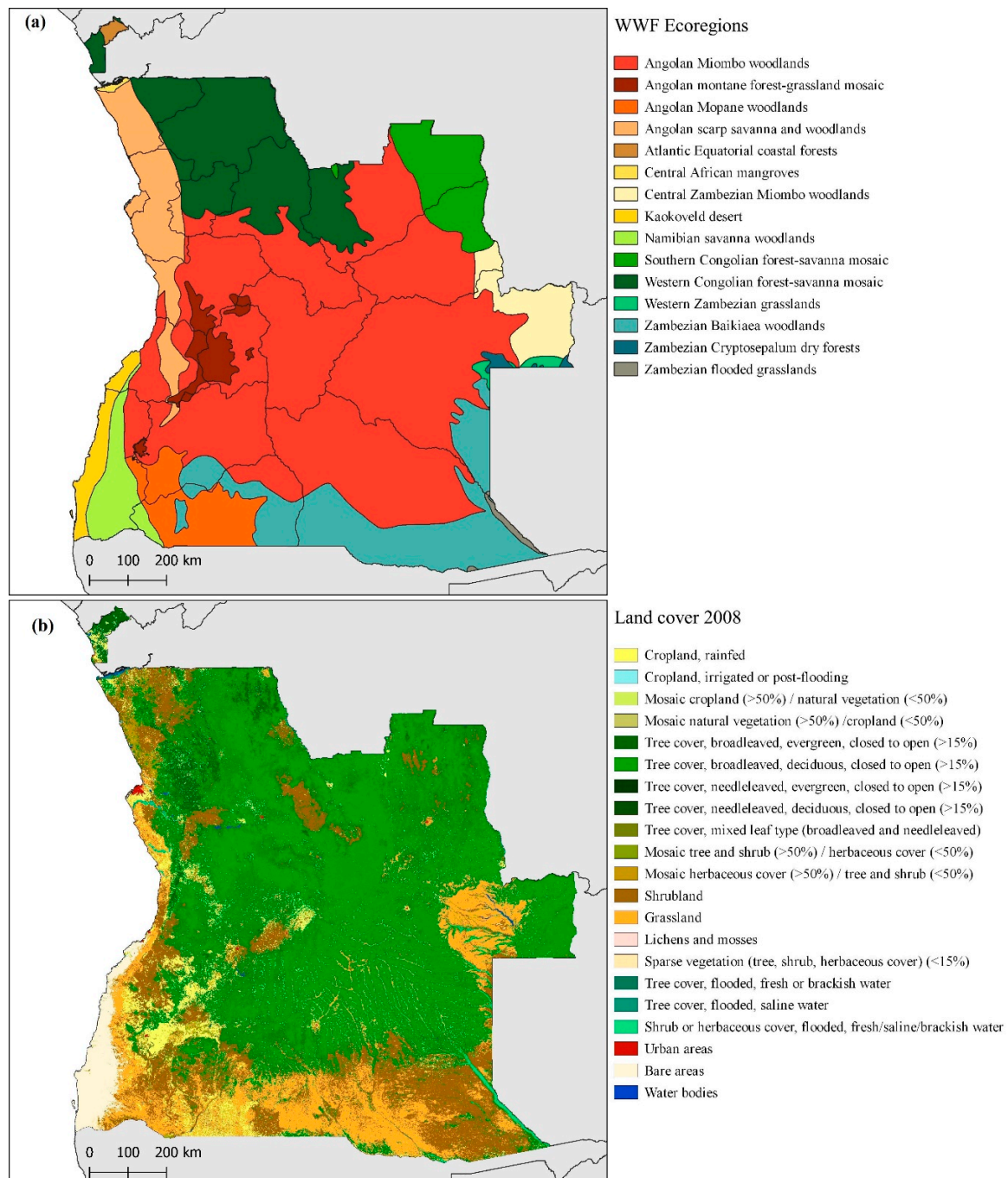
Figure 2. World Wildlife Fund (WWF) ecoregions and land cover map of Angola: (**a**) WWF ecoregions occurring in Angola [20]. The black lines represent the boundaries of the 18 provinces of Angola; (**b**) land cover map of Angola in 2018 (300 m resolution) adapted the European Space Agency (ESA) Climate Change Initiative Land Cover (CCI-LC) project [70].

3. Results

3.1. Area Burnt in Angola since 2001

Our results revealed that Angola has been extensively affected by fires every year. On average, ca. 368,300 km^2 burn every year since 2001, corresponding to 30% of the country's area. The highest values of burnt area were recorded between 2003 and 2005, with more than 400,000 km^2 burnt each year, and the lowest value was 315,580 km^2 in 2018 (Figure 3a).
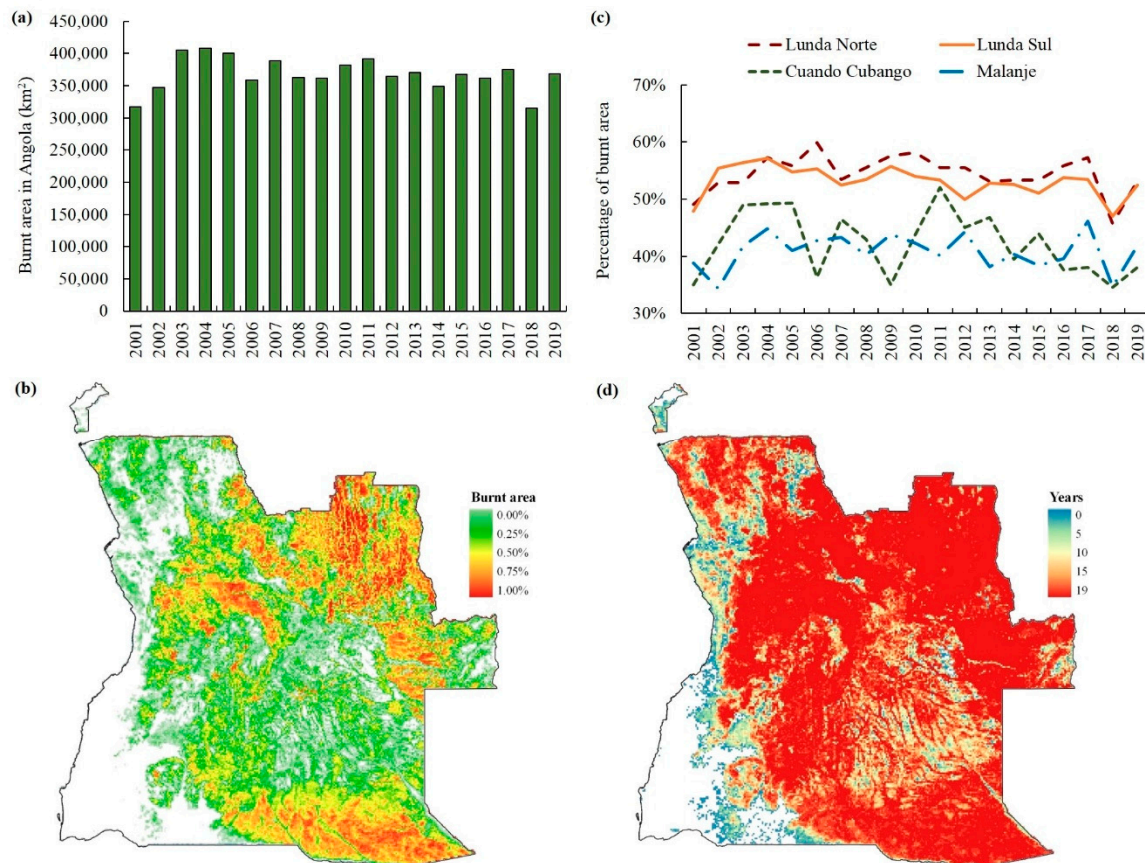
Figure 3. Burnt area in Angola, from 2001 to 2019: (**a**) Absolute burnt area (km²) per year; (**b**) map of the mean annual fraction of burnt area in each cell (5 km resolution); (**c**) percentage of the area burnt in the four provinces with the highest values; (**d**) map of the number of years when each cell was completely or partially burnt since 2001 (5 km resolution).

The northeast and southeast regions of Angola presented the highest percentage of annual burnt area per cell (Figure 3b). The provinces with the largest annual burnt areas were Lunda Norte (54%, ca. 58,840 km²), Lunda Sul (53%, ca. 41,375 km²), Cuando Cubango (42%, ca. 84,455 km²), and Malanje (41%, ca. 33,586 km²) (Figure 3c, Table S1). Among them, Cuando Cubango showed the highest variations over consecutive years. The most affected municipalities were Lubalo, Cuilo, and Lucapa in Lunda Norte; Saurimo and Muconda in Lunda Sul; Dirico and Rivungo in Cuando Cubango; and Luquenbo and Cangandala in Malanje. Intermediate values were found in Cuanza Sul, Moxico, Bié, Cunene, Cuanza Norte, Huambo, Zaire, Huíla, Uíge, and Benguela, with 12–30% of area burnt every year. The provinces of Bengo, Cabinda, Luanda, and Namibe had the lowest values, under 10%. Fire events are recurrent in Angola, except in the arid southwestern region. Figure 3d shows the number of years when each cell burnt totally or partially between 2001 and 2019. Since 2001, 64% of the cells burnt 15 years or more.

3.2. Spatial Trends of Burnt Area in Angola since 2001

The results of the contextual Mann–Kendall test highlights large areas of significant increasing and decreasing trends in the burnt area of Angola. Figure 4 shows the results of this test, where the red cells represent increasing trends (positive Z value) and green cells represent decreasing trends (negative Z values). The significant areas with a confidence level of 95% are outlined with a black line. The Mann–Kendall test was also performed (Figure S1), but the contextual Mann–Kendall test (Figure 4) performed better in creating larger and more homogenous clusters of cells corresponding to significant areas.
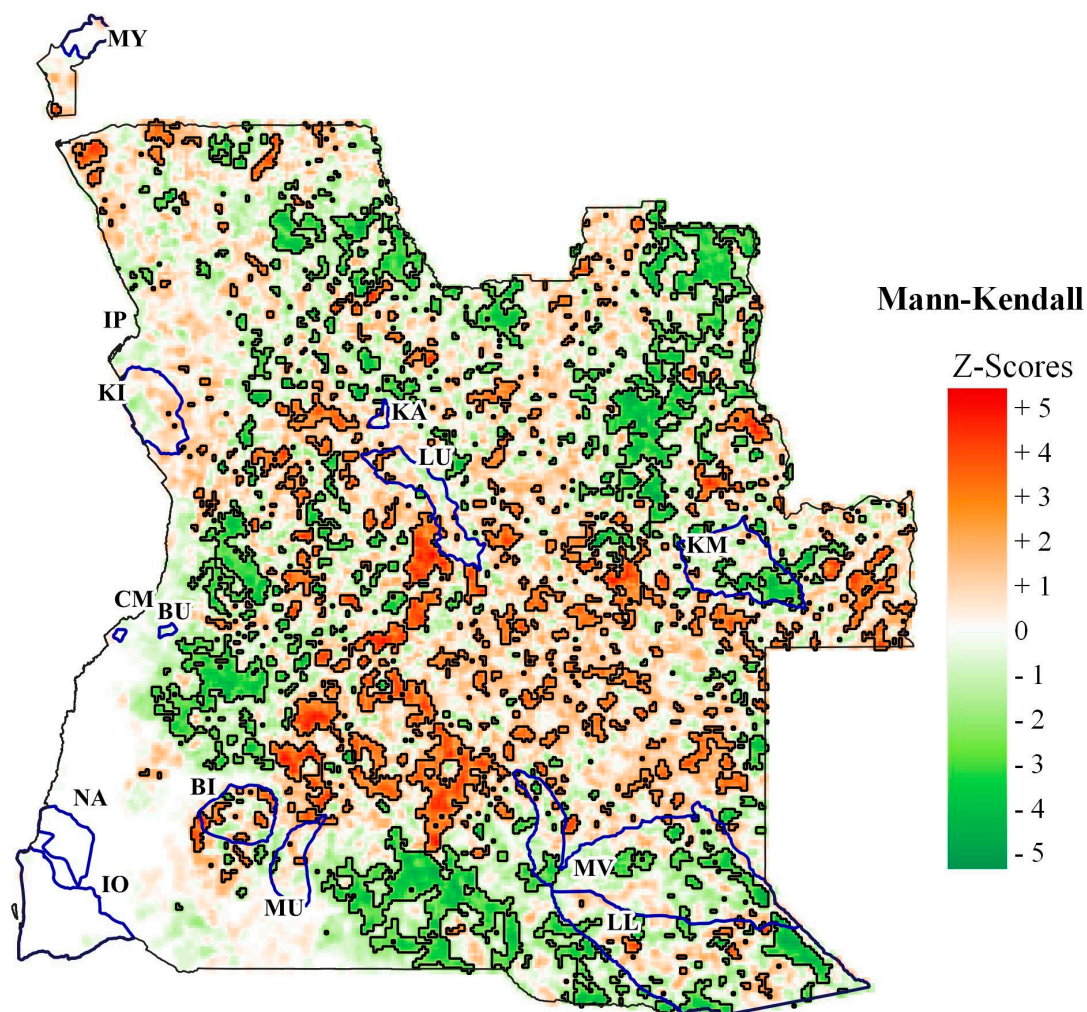
Figure 4. Trends of the annual burnt area in Angola for the 2001–2019 period, based on the contextual Mann–Kendall test. The positive z-scores correspond to areas of increasing trends of burnt area, while the negative z-scores correspond to decreasing trends. The significant areas (with a confidence level of 95%) were outlined with black lines. Protected areas are indicated with blue outlines: BI, Bicuar; BU, Búfalo; KA, Cangandala; CM, Chimalavera; IO, Iona; IP, Ilheu dos Pássaros; KM, Cameia; KI, Quiçama; LL, Luengue-Luiana; LU, Luando; MV, Mavinga; MU, Mupa; MY, Maiombe; NA, Namibe.

We detected significant areas of increasing trends in ca. 119,410 km^2 (10% of the country's area), mainly in the central region of the country. With more than 9400 km^2, the single largest area is located in the north of the Cuando Cubango province, and the second largest area, with ca. 4330 km^2, is found in Bié. The provinces with the most extensive areas of significant positive trends are Moxico (34,731 km^2), Cuando Cubango (18,628 km^2), Bié (15,830 km^2), and Huíla (12,658 km^2) (Figure 5, Table 1). Significant areas of decreasing trends was detected in ca. 154,240 km^2 (12% of the country's area), spread all across Angola, except in its central region. The single largest area has more than 21,800 km^2 and covers part of the Cuando Cubango and Cunene provinces; the second largest single area has approximately 14,000 km^2 and is located in Lunda Sul. The provinces with the most extensive areas of significant negative trends are Cuando Cubango (34,584 km^2), Lunda Sul (21,049 km^2), and Lunda Norte (19,353 km^2) (Figure 5, Table 1).
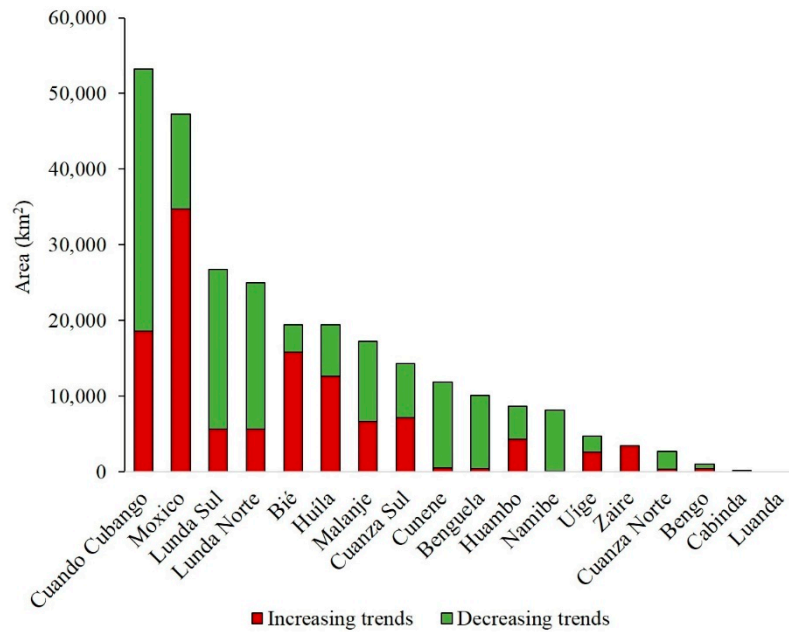
Figure 5. Areas of significant increasing and decreasing trends in Angolan provinces.

Table 1. Area and proportion of increasing and decreasing significant trends of annual burnt area in Angolan provinces, WWF ecoregions, and protected areas, from 2001 to 2019.

Provinces	Total Area	Area of Decreasing Trend		Area of Increasing Trend	
	(km^2)	(km^2)	(%)	(km^2)	(%)
Bengo	34,363	579	1.7	425	1.2
Benguela	39,509	9689	24.5	459	1.2
Bié	72,048	3625	5.0	15,830	22.0
Cabinda	7119	0	0.0	188	2.6
Cuando Cubango	199,483	34,581	17.3	18,628	9.3
Cuanza Norte	23,823	2301	9.7	381	1.6
Cuanza Sul	55,257	7196	13.0	7149	12.9
Cunene	77,259	11,347	14.7	545	0.7
Huambo	33,133	4391	13.3	4303	13.0
Huíla	78,684	6769	8.6	12,658	16.1
Luanda	2447	0	0.0	0	0.0
Lunda Norte	107,973	19,353	17.9	5639	5.2
Lunda Sul	77,927	21,049	27.0	5680	7.3
Malanje	82,163	10,645	13.0	6641	8.1
Moxico	199,986	12,506	6.3	34,731	17.4
Namibe	57,911	8100	14.0	82	0.1
Uíge	62,005	2102	3.4	2610	4.2
Zaire	36,590		0.0	3461	9.5
WWF ecoregions					
Angolan Miombo woodlands	628,703	64,488	10.3	86,310	13.7
Angolan montane forest-grassland mosaic	25,419	8251	32.5	1172	4.6
Angolan mopane woodlands	51,064	1344	2.6	1045	2.0
Angolan scarp savanna and woodlands	73,947	3375	4.6	2552	3.5
Atlantic Equatorial coastal forests	2534	0	0.0	0	0.0
Central African mangroves	1240	0	0.0	326	26.3
Central Zambezian Miombo woodlands	40,648	1769	4.4	6633	16.3
Kaokoveld desert	20,590	0	0.0	0	0.0
Namibian savanna woodlands	33,491	0	0.0	0	0.0
Southern Congolian forest-savanna mosaic	58,558	18,693	31.9	3208	5.5
Western Congolian forest-savanna mosaic	168,864	23,118	13.7	9698	5.7
Western Zambezian grasslands	4606	133	2.9	1134	24.6
Zambezian Baikiaea woodlands	131,010	32,382	24.7	6559	5.0
Zambezian Cryptosepalum dry forests	3085	0	0.0	776	25.1
Zambezian flooded grasslands	3197	681	21.3	0	0.0

Table 1. *Cont.*

Provinces	Total Area	Area of Decreasing Trend		Area of Increasing Trend	
	(km²)	(km²)	(%)	(km²)	(%)
Protected Areas					
Bicuar National Park	7728	162	2.1	1809	23.4
Bufalo Partial Reserve	332	0	0.0	0	0.0
Chimalavera Natural Regional Park	214	0	0.0	0	0.0
Ilha dos Pássaros Integral Nature Reserve	0	0	0.0	0	0.0
Iona National Park	15,264	0	0.0	0	0.0
Cameia National Park	14,185	3918	27.6	161	1.1
Cangandala National Park	642	0	0.0	33	5.1
Quiçama National Park	8597	0	0.0	42	0.5
Luando Integral Nature Reserve	8737	48	0.5	769	8.8

3.3. Burnt Area Trends According to WWF Ecoregions, Protected Areas, and Land Cover

Our results revealed a very uneven distribution of burnt area trends across WWF ecoregions (Figure 6a, Figure S2, and Table 1). Central African mangroves and Zambezian Cryptosepalum dry forests are among the smallest ecoregions occurring in Angola, but they displayed the highest percentage of increasing trends, and no significant decreasing trends. Western Zambezian grasslands, Central Zambezian Miombo woodlands, and Angolan Miombo woodlands also showed very high percentages of increasing trends (25%, 16%, and 14%, respectively) and much lower percentages of decreasing trends (3%, 4%, and 10%, respectively). The Angolan Miombo woodlands is the largest ecoregion (more than 628,000 km²), covering the central region of Angola.

The high percentage of decreasing trends was found in the Angolan Montane forest-grassland mosaic (32%), the Southern Congolian forest-savanna mosaic (32%), the Zambezian Baikiaea woodlands (25%), the Zambezian flooded grasslands (21%), and the Western Congolian forest-savanna mosaic (14%). The Namibian Savanna woodlands, Kaokoveld desert, and Atlantic Equatorial coastal forests exhibited no significant trends of burnt area.

In protected areas, burning trends are mainly negative. Our results revealed areas of decreasing trends in five national parks, totaling ca. 19,560 km², which represents 12% of the national protected area (Figure 4, Table 1). Cameia has the highest percentage of decreasing trends (28%, 3918 km²), followed by Luengue-Luiana (18%, 7811 km²) and Mavinga (17%, 7466 km²) national parks (Figure 6b). The area of increasing trends was ca. 5710 km², corresponding to 4% of the global protected area. It was detected in eight protected areas and the highest proportion was found in Bicuar National Park (23% of the park's area, 1809 km²) (Figure 6b, Table 1). Luando reserve (9%, 769 km²), Cangandala (5%, 33 km²), Mupa (5%, 240 km²), and Luengue-Luiana (4%, 1949 km²) national parks also have important fractions of increasing trends. Some national parks, such as Namibe, Iona, and Maiombe, showed no significant trend.

Concerning the land cover, Angola is covered mainly by natural vegetation as forest, shrubland, and grassland. In 2018, forest (including broadleaved, deciduous, evergreen, and flooded tree classes) was found in 59% of the country's area, shrubland in 18% and grassland in 12% (Figure 7a). Cropland was identified in ca. 48,900 km², representing only 4% of the territory. Comparing the composition of the areas included in the significant clusters, clusters with increasing trends presented a much higher fraction of forest classes (80%) than clusters with decreasing trends (55%). In clusters with decreasing trends, the proportions of grassland and shrubland were much higher (20% and 19%, respectively) than in the increasing ones (4% and 10%, respectively) (Figure 7a and Figure S3).
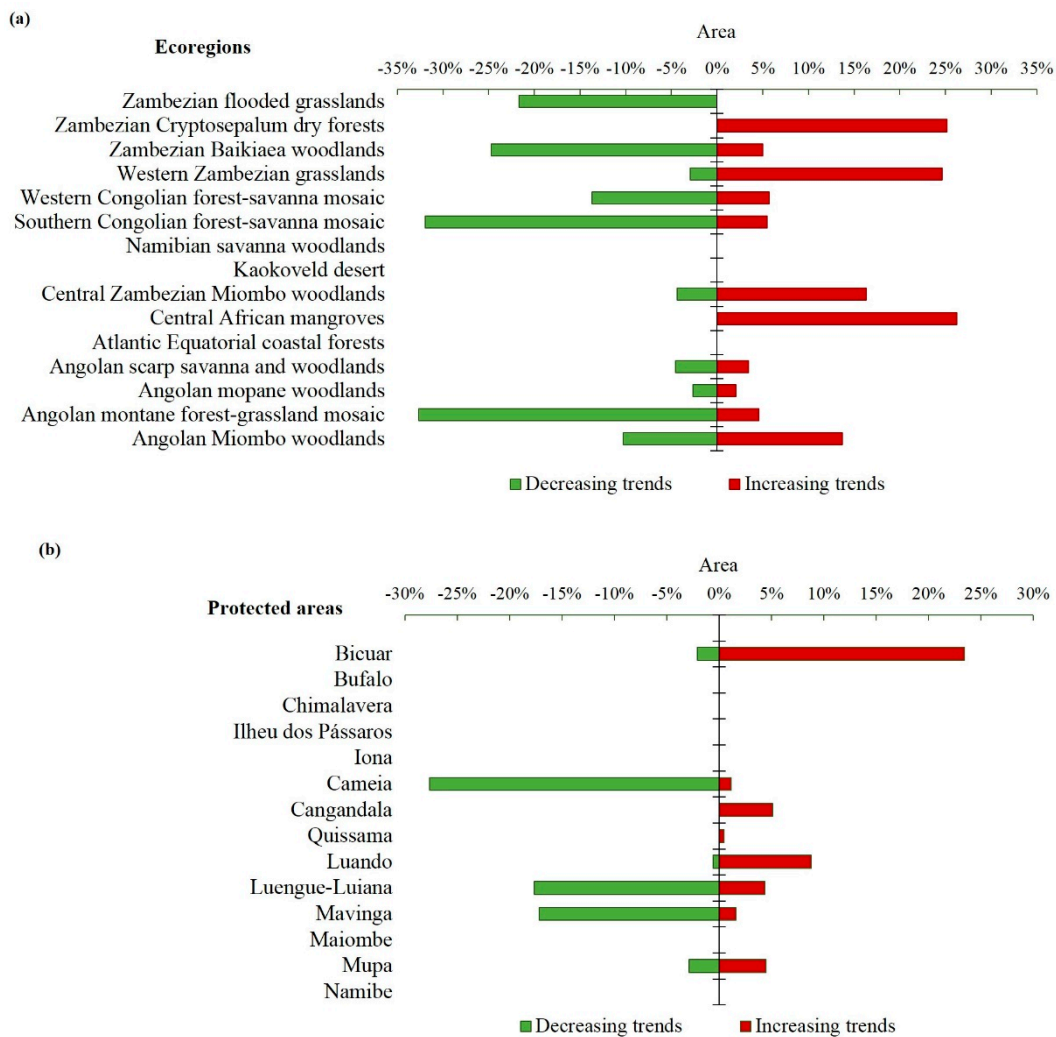
Figure 6. Areas (%) of significant increasing and decreasing trends: (**a**) in WWF ecoregions; (**b**) in protected areas.

Areas with significant increasing and decreasing trends show similar patterns of land cover changes since 2002 (Table 2), occurring a global decrease in natural vegetation extent, i.e., grassland, shrubland, and forest, as well as an increase in cropland and urban areas (Figure 7). In significant clusters, forest shows a small increase in area between 2002 and 2006, but after 2006 it decreases and reaches the lowest value in 2018. Shrubland has maintained almost stable since 2010, with a small increase during the last four years in clusters with decreasing trends. Between 2002 and 2018, clusters with increasing trends have lost of 0.04% of forest, 0.38% of shrubland, and 1.26% of grassland, but displayed an increase of cropland (8.84%). Decreasing trend clusters lost 0.13% of forest area, 0.40% of shrubland and 1.19% of grassland, and has a great increase of cropland by 15.87% (Figure 8). Urban areas represented a small fraction inside the clusters, but they have a great increase, mainly in clusters with decreasing trends.
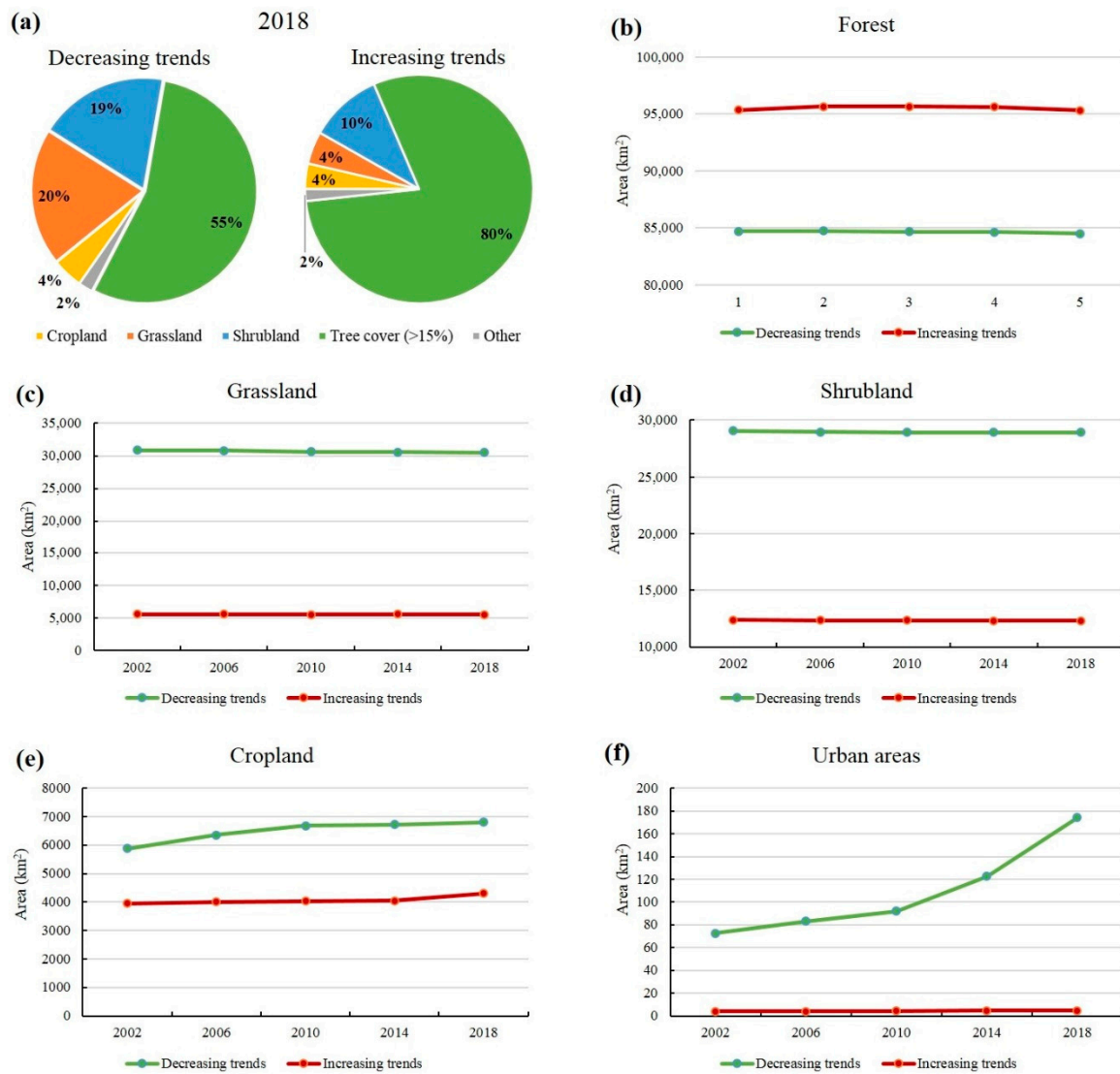
Figure 7. Land cover and the significant trends of burnt areas from 2002 to 2018, in increasing and decreasing trends clusters: (**a**) Proportions of the main land cover classes in 2018 (the last year for which information is available); (**b**) area of forest; (**c**) area of grassland; (**d**) area of shrubland; (**e**) area of cropland; (**f**) area of urban areas.
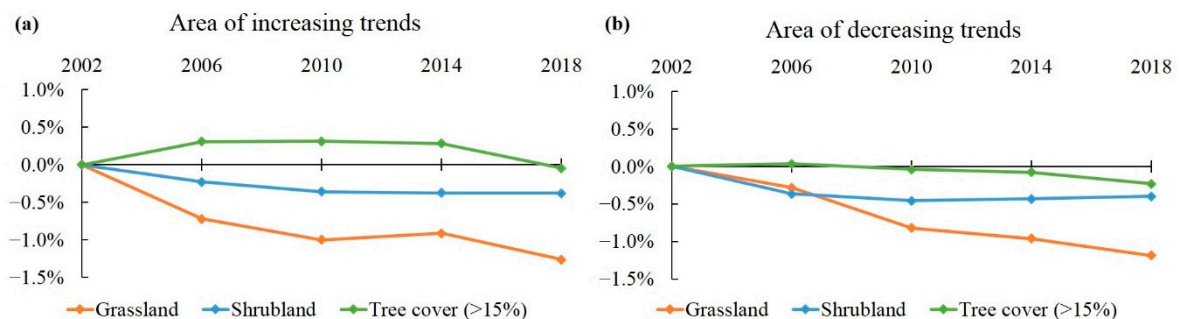

Figure 8. Changes in area of natural land cover classes (grassland, shrubland and forest) since 2002 to 2018, (**a**) in increasing trends clusters, and (**b**) in decreasing trend clusters.

Table 2. Area of land cover classes within the significant clusters of burnt area trends, in 2002, 2006, 2010, 2014, and 2018.

Land Cover Class	Area of Decreasing Trends						Area of Increasing Trends					
	2002 (km²)	2006 (km²)	2010 (km²)	2014 (km²)	2018 (km²)	Change 2001–2018 (km²)	2002 (km²)	2006 (km²)	2010 (km²)	2014 (km²)	2018 (km²)	Change 2001–2018 (km²)
Bare areas	0	0	0	0	0	0	2	2	2	2	2	0
Cropland, irrigated, or post-flooding	2	2	2	2	3	2	2	2	2	2	3	1
Cropland, rainfed	4153	4425	4581	4606	4656	503	2203	2239	2251	2251	2349	146
Grassland	30,162	30,081	29,904	29,859	29,795	−366	4938	4939	4928	4932	4942	4
Mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (<50%)	1720	1925	2094	2111	2148	428	1746	1760	1777	1792	1948	202
Mosaic herbaceous cover (>50%)/tree and shrub (<50%)	706	701	710	711	705	−1	621	580	575	576	547	−74
Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%)/cropland (<50%)	1759	1483	1382	1379	1394	−365	1039	693	673	659	684	−355
Mosaic tree and shrub (>50%)/herbaceous cover (<50%)	1054	1008	1015	1015	1032	−22	603	620	632	653	682	78
Shrub or herbaceous cover, flooded, fresh/saline/brackish water	467	471	484	481	497	30	441	440	446	447	458	17
Shrubland	29,043	28,936	28,910	28,916	28,927	−116	12,364	12,336	12,320	12,318	12,317	−47
Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	83	83	83	83	83	0	0	0	0	0	0	0
Tree cover, broadleaved, deciduous, closed to open (>15%)	82,910	82,938	82,870	82,837	82,696	−214	94,565	94,827	94,829	94,801	94,493	−72
Tree cover, broadleaved, evergreen, closed to open (>15%)	1753	1753	1756	1758	1770	17	762	789	788	790	784	22
Tree cover, flooded, fresh, or brackish water	51	52	53	52	52	1	8	12	13	13	13	5
Tree cover, flooded, saline water	0	0	0	0	0	0	10	13	13	13	14	4
Urban areas	73	83	92	123	174	101	4	4	4	5	5	1

4. Discussion

4.1. Trends of Annual Burnt Area in Angolan Provinces and Ecoregions

This study presents a spatial and temporal analysis of the area burnt in Angola based on MODIS satellite images collected from 2001 to 2019, which allows us to assess the main trends over the years. Our results unveiled new information about fire in Angola, revealing the main areas of increasing and decreasing trends of the annual burnt area. There are several studies on fire regimes and dynamics at the global scale or focused in southern Africa (e.g., [17,18,42,77,78]); however, this is the first study on fire trends carried out specifically in Angola and focused on its ecosystems and protected areas. This country encompasses unique habitats and species, and is possibly one of the least documented biodiversity hotspot areas in the world [79]. However, with continued population growth and lack of financial support, subsistence agriculture and human pressure on the land will continue to increase, putting high pressure on natural resources [19,34,51] and endangering the conservation of the Angolan natural heritage [37,47].

The highest values of burnt area were recorded between 2003 and 2005, which may be a consequence of the end of the civil war. During the civil war, ca. one million people were killed and over four million people displaced. Moreover, there was a massive migration from rural communities to the cities and fields were abandoned [80,81]. When the war ended, some displaced people returned to rural areas and burnt natural vegetation to clear land for agriculture.

The largest burnt areas and the highest frequency of fire were found in grasslands and savannas of Lunda Norte, Lunda Sul, and Malanje (northeast Angola), as well as in open savannas of Cuando Cubango (southeast Angola). This agrees with previous studies that recognized these regions as the most affected by fires in Angola [15,17,23,77]. However, these provinces presented small areas of increasing trends and the largest clusters of decreasing trends of burnt area, suggesting a possible decrease in fire extent and/or frequency in the coming years, if the current trends are maintained. Lunda Norte and Lunda Sul are formed mainly by vast plains drained by the tributaries of the Cassai–Congo Basin [46]. According to the Köppen–Geiger climatic classification, the climate is humid tropical and tropical savanna, with hot and humid summers, and warm and dry winters [82]. The population density and the practice of agriculture are very low, but the wind plays an important role in the occurrence of fires, drying the grasslands [49,83]. Cuando Cubango is composed mainly of Kalahari sands, as it is a vast plain with slow flowing rivers. The climate is humid subtropical in the north and hot semi-arid in the south, with a low average annual rainfall, ranging from 1000 to 600 mm [46,82]. The population density is low in this region but more than half of the people work in agricultural activities [49]. Malanje has a similar pattern, with low population density but high intensity of agricultural activities [4]. This province includes a plateau in its central region, with elevation from 1000 to 1250 m, and the climate is tropical savanna [46,82].

The main areas of increasing trends were found in central Angola. This region includes Cuanza Sul, Bié, Huambo, Moxico, and Huíla provinces, and consists mainly of Angolan Miombo woodlands. Moxico is located in central-eastern Angola, the mean annual rainfall ranges from 900 to 1300 mm and is dominated by a humid subtropical climate. Cuanza Sul, Bié, Huambo, and Huíla are located in the extensive region of the ancient plateau, characterized by high levels of annual precipitation in the central zone, reaching 1300 mm in the province of Huambo. [46,49,82]. These provinces are dominated by tropical savanna, humid subtropical, and oceanic climates [82]. Currently, they have a very high population density and a high fraction of families working in agriculture. The Angolan Miombo woodlands is an ecoregion almost exclusive to Angola, differing from other savannas and forests in its high abundance of trees of the Leguminosae family, specifically, *Brachystegia*, *Julbernardia*, and *Isoberlinia* [72,84]. Several authors recognized fire as one of the most important ecological factors in Miombo, preserving the balance between grasses and trees [11,85]. Most plant species of Miombo show some degree of fire resistance, yet they cannot survive intense and recurrent fires [11]. The natural cause of Miombo fires is mainly thunderstorms in the early rainy season, but most fires are caused by

human action and occur during the dry and hot season [11], when the grass fuel is drier, resulting in more intense, damaging fires. A continuous increase in burnt area for a long period could represent a serious threat for tree species, transforming Miombo woodlands into open savannas [23].

The Central Zambezian Miombo woodlands should also be a priority for future studies and fire management measures. The ecoregion is found in the eastern province of Moxico and show more than 16% of the area with significant increasing trends. Both ecoregions, the Angolan Miombo woodlands and the Central Zambezian Miombo woodlands, are included in the regional center of Zambezian endemism (defined by White [86]), housing a high richness and endemism of plant and animal species [72]. Fire is an integral part of the Miombo ecology, but changes in fire regimes, such as the increase in frequency or severity, can result in drastic landscape changes, reducing or removing some species. Zambezian Cryptosepalum dry forests, Western Zambezian grasslands, and Central African mangroves showed the highest percentage of increasing trends. However, these ecoregions are very little represented in the country, with less than 5000 km^2 each, and these results cannot be considered representative. Mangroves are present in a small area on the bank of the Congo River, surrounded by extensive areas of Angolan scrap savanna and woodlands. The cluster of growing trends detected in the mangrove area is shared with an extensive area of scrap savanna, suggesting that it may correspond to a commission error, resulting from the effect of the neighboring cells involved in the determination of trends. The same may be occurring with Zambezian Cryptosepalum dry forests and Western Zambezian grasslands, these ecoregions are surrounding by Angolan and Central Zambezian Miombo woodlands, which has large clusters of significant increasing trends of burnt area in transitional zones.

The WWF ecoregions show very clear patterns of increasing and decreasing trends in the area burnt. The ecoregions represent the original distribution of distinct assemblages of species and communities [20], better distinguishing the structural organization of the landscape than the generic vegetation classes. The definition of fire management measures and laws must be adapted to each ecoregion's characteristics, addressing socioeconomic and ecological problems that restore, protect, and maintain natural habitats.

4.2. Implications for Vegetation and Land Cover

The largest clusters of decreasing trends in burnt area are found in the regions most affected by fire events every year, such as Lunda Norte, Lunda Sul, and Cuando-Cubango. These regions have a lower percentage of forest (ca. 55%) and a large percentage of shrubland (19%) and grassland (20%), a pattern probably resulting from the recurrent fires identified in these provinces that limit the growth of trees and shrubs. In these clusters, there was also a strong increase in the extent of urban areas, which more than doubled from 2002 to 2018, and of cropland areas, which slowly but continuously has been growing over the years.

On the other hand, the areas of increasing trends are characterized by a large proportion of forest (ca. 80%) and small fractions of shrubland (10%) and grassland (4%). These areas also have a relatively high proportion of cropland (4%), which substantially increased since 2004. In these regions, the continuous increasing trend of the annual burnt area may lead to the conversion of forests and woodlands into grasslands and shrublands. Interestingly, Cuando Cubango is among the provinces that displays more areas of significant positive trends but also more areas of negative trends. This reveals high turnover of burnt areas in the province, possibly resulting in high levels of land cover changes.

Our findings show a reduction in forest cover over the years, which is in agreement with other studies [23,42], confirming that land cover changes in Africa have been dominated by woodland and forest losses. The fires have had severe effects on Angolan woodlands, converting large areas of forest and woodlands into open land [25]. For instance, a study by Palacios et al. [87] reported that 78.4% of Huambo province was covered by Miombo woodland in 2002, but 13 years later it had dropped to 48.3%. Similar losses in western Cuando Cubango, eastern Huíla, and eastern Huambo were reported by Schneibel et al. [88], and Mendelsohn and Mendelsohn [89]. However, the rate of forest loss detected

in this study appears to be much lower than the rate reported by Hansen et al. [30], as reported by Food and Agriculture Organization of the United Nations (FAO) [31,90] and Global Forest Watch [32]. Other studies of land cover change [91,92] have also detected a much lower estimate of total forest area and forest loss when using ESA CCI-LC maps. One possible explanation is the different data sources. FAO collected forest resource data from the member countries [31], using satellite imagery and field surveys in different countries, while Hansen et al. [30] used high spatial resolution satellite data (30 m) obtained from NASA's Landsat, which allows for the detection of small-scale forest clear cuts. The different fraction of canopy considered in the forest definitions is also a possible cause of the disparity in the results. FAO [31] adopted a definition >10% canopy cover, while Global Forest Watch defined >30% canopy cover as forest. In our study, forest is defined as areas with >15% canopy cover, which does not reflect the decrease in the percentage of tree cover within each area, unless it falls below 15% of coverage.

The expansion of shifting cultivation practiced by smallholders and the overexploitation for timber, fuelwood, and charcoal are possibly the most important factors driving the rapid loss of Angolan woodlands and forests, as well as their very slow recovery rate [23]. The relative lack of nutrients and moisture in soils forces the farmers to leave their fields and use fire to clear new fields and enrich the soil with nutrients from the ash of the woody biomass [93]. The rate at which the woodlands are cleared and converted into cropland is dependent on the need to feed a growing human population. To reduce the impacts of human activity on fire processes, management strategies should be urgently implemented. These strategies must incorporate the ecological and socio-economic roles of fire, as well as the conservation of Angolan ecosystems [16].

4.3. Conservation and Management of Protected Areas

The protected areas system shows a strong impact on the burnt areas, presenting larger clusters of decreasing trends than of increasing trends. For instance, Cameia, Luengue-Luiana, and Mavinga national parks are located in eastern Angola (Moxico and Cuando Cubango provinces) and have the largest areas of decreasing annual burnt area. The decreasing trends detected in these areas may be related to the increase in the number of herbivores after the civil war. For instance, a study carried out in Luiana National Park showed a rapid increase in the numbers of African elephants between 2004 and 2005 [94]. According to Goldammer and Ronde [11], the abundance of mammalian herbivores is an important determinant of fire intensity. When the number of herbivores is high, less fuel is available and fires can affect smaller areas, with lower intensities [11,95].

Bicuar National Park is the most worrying protected areas, with increasing trends in more than 23% of its area. It is the only protected area of Huíla, located in a transition zone between the Angolan Miombo woodlands and the Zambezian Baikiaea woodlands ecoregions. With an area of almost 8000 km^2, it consists mainly of riverbanks of the Cunene River, sandy hills, and river valleys with savannah grasslands. It was created in 1938 as a hunting reserve due to the abundance of game species, such as African bush elephant (*Loxodonta africana*), blue wildebeest (*Connochaetes taurinus* subsp. *taurinus*), and eland (*Tragelaphus oryx*) [96]. The analysis of Luando Integral Nature Reserve also reveals significant increasing trends in ca. 9% of this area. The status of protected area was acquired in 1955, to conserve the giant sable antelope (*Hippotragus niger* subsp. *variani*) [97], including more than 8000 km^2 of the Angolan Miombo woodlands.

Angolan protected areas need a real and efficient administration, in addition to integrated biodiversity management plans. In 2006, the National Parks of Quissama, Mupa, Cangandala, Iona, Cameia, and Bicuar were almost completely abandoned, without equipment or supervision [98]. Parts of these protected areas are occupied by human populations that hunt and burn without control, leading to the disappearance of large mammals and converting large areas into agricultural land [78]. However, the Protected Areas system was greatly expanded in 2011 and more resources are being made available for more effective management [46]. The difficulties imposed by limited budgets, scarce

human resources, and weak technical capacity impose the need to identify priority areas, where the government's conservation resources must be allocated first.

Fires have been the main management tool used in protected areas of the African savanna [95]. During the 20th century, managers of protected areas have considered both the suppression of unwanted fires and ignition of prescribed fires to achieve different goals, such as reducing the putative negative effects of fire on ecosystems, reducing the risk of unplanned fires, improving visibility for game viewing and policing, improving forage quality, and fighting invasive alien species [95,99–101]. Fire managers must decide how, where, and when to apply fires to achieve their goals of management, while also respecting legal constraints. During the 21st century, fire management in Angola will face new challenges imposed by the effects of climate change and a growing human population.

5. Conclusions

In this study, we detected spatial and temporal patterns of burnt areas across Angola, which is a crucial step for the definition of conservation priorities and management strategies. The identification of the areas with significant trends is extremely important in tropical areas with low field data available and few human and financial resources, as is the case of Angola. This will allow for efficient distribution of fire management resources and public investment, resulting in improved management of Angolan vegetation.

Understanding the role of climatic and anthropogenic factors on these trends is very important. The overexploitation of forests for the production of timber, firewood, and charcoal also enhances grass development, which in turn promotes more intense fires in the dry season. Effective actions to limit fire events are urgently needed to protect fire-sensitive resources, natural ecosystems, and to reduce carbon emissions to the atmosphere. While most southern African countries have legislation and regulations to use and control fire, these are rarely applied due to enforcement difficulties [11]. Fire control is also difficult because, in Africa, fires occur in thousands of small, dispersed events. Moreover, climate change will bring more frequent and intense droughts to Angola, with strong impacts on water resources, agricultural productivity, and wildfire potential. All of these factors are expected to play an important-negative-role on the trends of burnt areas, land cover change, and biodiversity conservation.

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