Increasing Fire Activity in African Tropical Forests is Associated with Land Use and Climate Change

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Abstract

Fires were historically rare in tropical forests of West and Central Africa, where dense vegetation, rapid decomposition, and high moisture limit available fuels. However, increasing heat and drought combined with forest degradation and fragmentation are making these areas more susceptible to wildfire. We evaluated historical patterns of MODIS active fires in African tropical forests from 2003-2021. Trends were mostly positive, particularly in the northeastern and southern Congo Basin, and were concentrated in areas with high deforestation. Year-to-year variation of fires was synchronized with increasing temperature and vapor pressure deficit. There was anomalously high fire activity across the region during the 2015-2016 El Niño. These results contrast sharply with the drier African woodlands and savannas, where fires have been steadily decreasing. Further attention to fires in African tropical forests is needed to understand their global impacts on carbon storage and their local implications for biodiversity and human livelihoods.

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Increasing Fire Activity in African Tropical Forests is Associated with Land Use and Climate Change

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Key Points:

- Active fire detections increased from 2003-2021 across Central Africa, with positive fire trends concentrated in the Congo Basin.
- Positive fire trends were associated with deforestation and were synchronized with increasing temperature and vapor pressure deficit.
- There was higher-than-usual fire activity in tropical Africa forests associated with the strong 2015-2016 El Niño event.

Abstract

Fires were historically rare in tropical forests of West and Central Africa, where dense vegetation, rapid decomposition, and high moisture limit available fuels. However, increasing heat and drought combined with forest degradation and fragmentation are making these areas more susceptible to wildfire. We evaluated historical patterns of MODIS active fires in African tropical forests from 2003-2021. Trends were mostly positive, particularly in the northeastern and southern Congo Basin, and were concentrated in areas with high deforestation. Year-to-year variation of fires was synchronized with increasing temperature and vapor pressure deficit. There was anomalously high fire activity across the region during the 2015-2016 El Niño. These results contrast sharply with the drier African woodlands and savannas, where fires have been steadily decreasing. Further attention to fires in African tropical forests is needed to understand their global impacts on carbon storage and their local implications for biodiversity and human livelihoods.

Plain Language Summary

Most of the global area burned by wildfires is in the dry savanna and grassland ecosystems of Africa. In contrast, fires have historically been rare in the wetter tropical forests of West and Central Africa. However, these forests are becoming more vulnerable to fire because climate change is increasing temperatures and drought stress in the tropics. Human activities such as agriculture, logging, and mining are also fragmenting the remaining forests and make them more susceptible to fire. We used measurements of actively burning fires from Earth observing satellites to study how the amount of fire in African tropical forests has changed from 2003-2021. There were several areas with strong trends of increasing fire, mainly in the Congo Basin. In contrast, there were almost no locations where fire was decreasing. The increasing fire trends occurred in locations where deforestation was occurring and climate was becoming warmer and drier. During 2015-2016 a strong El Niño global weather pattern was associated with higher-than-normal fire activity throughout the tropical forests in West and Central Africa. Increasing fire is a concern because it can release greenhouse gasses into the atmosphere, reduce the amount of carbon stored in the African tropicals, degrade habitats for species that live in tropical forests, and decrease the amounts of wood, food, medicine and other resources that forests provide for humans.

1 Introduction

Africa is known as the “fire continent”, containing approximately two-thirds of the annual global burned area measured by satellite remote sensing (Giglio et al., 2018). These fires account for more than half of the total global carbon emissions (Van Der Werf et al., 2017). Most African wildfires occur in the savanna ecoregions, which have long dry seasons combined with continuous grass fuelbeds and widespread human use of fire for land management (Archibald, 2016). Savanna fires often occur annually and have a stabilizing influence that maintains widespread grass cover and low tree densities (Staver et al., 2011). In contrast, tropical forests have denser tree canopies, more woody fuels, higher precipitation, and shorter dry seasons that result in higher fuel moisture and make them more resistant to fire spread (Cochrane, 2003). When fires do occur in tropical forests, they can cause substantial tree mortality that reduces canopy cover and alters understory fuels and microenvironments. These changes initiate positive feedbacks between fire and forest structure that drive forest degradation and can result in eventual conversion to fire-maintained grasslands and shrublands (Dwomoh & Wimberly, 2017a). Because forest fires are generally smaller and more episodic than savanna fires, they tend to be overlooked in broader continental assessments of African fire regimes. In this study, we used long-term satellite records to explore the spatial distribution and trends of fire across Africa's forest ecoregions, and we assessed the influences of deforestation and climate variation on these patterns.

African forests are a major constituent of the tropical carbon sink, sequestering more carbon per year than Amazonia (Hubau et al., 2020). The forest carbon sink in Africa has shown less of a decline than Amazonia over the past three decades, and this difference has been attributed to lesser impacts of drought and extreme temperatures in Africa than in Amazonia. Another study by Bennett et al. (2021) found that the 2015-2016 El Niño has relatively minor impacts on tree mortality and growth across tropical Africa and suggested that African forests may be more resilient to droughts than forests in Amazonia and Asia. Both studies were based on data from long-term forest monitoring plots, and neither directly addressed the impacts of wildfires and their responses to climate variation. African forests will be subjected to greater climate stresses in the future, including increasing temperatures (Weber et al., 2018) and more extreme cycles of deluge and drought (Haile et al., 2020; Sylla et al., 2016). Thus, further research is needed on the climate resilience of African forests, and in particular there is a need to better understand how changing climate and land use may influence future fire regimes.

Although fires are generally assumed to be uncommon in moist tropical forests, the potential for degradation, fragmentation, and droughts to increase susceptibility to fire has long been recognized (Cochrane et al., 1999). In Africa, the occurrence of fire measured as burned area or point detections of active fires is much lower in forests than in savannas (Dwomoh & Wimberly, 2017b; Zubkova et al., 2019). However, there is also evidence of wildfires outbreaks throughout tropical Africa. In southern Ghana, large areas of tropical forest reserves were burned in the 1980's following the exceptional El Niño of 1982-1983 (Hawthorne, 1994; Hawthorne & Abu-Juam, 1995). Following the most recent strong El Niño in 2015-2016, large forest fires resurged in Ghana (Dwomoh et al., 2019) and the northern Republic of Congo (Verhegghen et al., 2016). Fire was found to be an important driver of forest degradation in the Democratic Republic of Congo, with increasing trends of fire frequency in central and western parts of the country (Shapiro et al., 2021). Although there is evidence that wildfires are impacting tropical forests throughout the continent, to date there have been no comprehensive fire assessments focused on African tropical forests.

To address this knowledge gap, we explored the spatial and temporal patterns of remotely sensed active fire detections across tropical Africa and analyzed their associations with potential drivers. Our specific objectives were to identify locations where fire frequency increased or decreased over the past two decades, assess whether these changes were associated with climate or land use, determine whether fire trends occurred in locations with particular environmental characteristics, and highlight locations where the 2015-2016 El Niño was associated with wildfire outbreaks.

2 Materials and Methods

2.1 Study area

Our study domain was the moist tropical forests of West and Central Africa. We identified forested areas using the baseline 2000 percent cover map from the Global Forest

Change dataset version 1.9 (Hansen et al., 2013). These 30 m resolution data were summarized using a grid of 0.05-degree cells. All Landsat pixels with forest cover greater than 50% were classified as forest. All 0.05-degree cells with more than 50% forested Landsat pixels were included in the analysis. We also extracted all ecoregions that were classified as Tropical and Subtropical Moist Broadleaf Forests and located in West or Central Africa from the Terrestrial Ecoregions of the World dataset (Olson et al., 2001). Ecoregion boundaries were overlaid on maps of the analysis results to provide a geographic reference, and they were used to generate zonal summaries of change. The final study area included 205 million ha that were classified as forest in 2000 and fell within the forest ecoregions (Figure 1). It extended from the Western Guinean Lowland Forest region in West Africa along the Atlantic Coast and across Central Africa to the Albertine Rift Montane Forests along the eastern edge of the Democratic Republic of Congo.

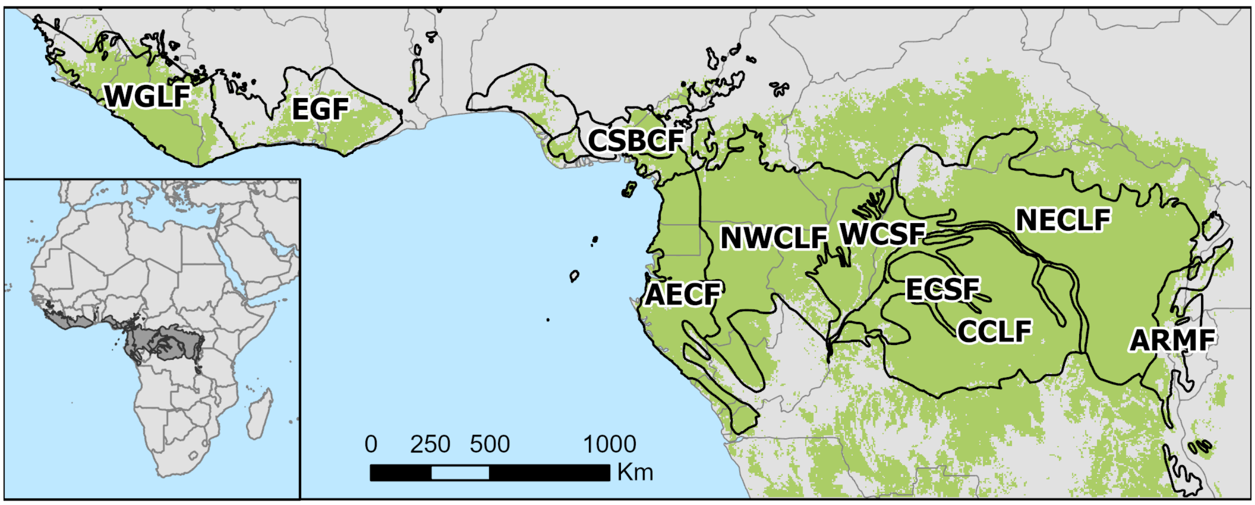

Figure 1. Study area encompassing locations with > 50% forested land cover (green shading) falling within the Tropical and Subtropical Moist Broadleaf Forests of West and Central Africa (Black Lines). The ten ecoregions with the highest area of forest land cover are labeled. AECF = Atlantic Equatorial Coastal Forests; ARMF = Albertine Rift Montane Forests, CCLF = Central Congolian Lowland Forests, CSBDF = Cross-Sanaga-Bioko Coastal Forests, ECSF = Eastern Congolian Swamp Forests, EGF = Eastern Guinean Forests, NECLF = Northeast Congolian Lowland Forests, NWCLF = Northwest Congolian Lowland Forests, WCSF = Western Congolian Swamp Forests, WGLF = Western Guinean Lowland Forests.

2.2 Data

MODIS Terra (MOD14) and Aqua (MYD14) Collection 6.1 active fire (Giglio et al., 2016) were obtained from the NASA Fire Information for Resource Management System (FIRMS). These data had a spatial resolution of 1 km^2 and covered the years 2003-2021 during which both Terra and Aqua satellites operational. Fires that were identified with low confidence (< 30%) were excluded from the dataset. Forest loss data from 2002-2021 with a spatial resolution of 30 m were obtained from the Global Forest Change dataset version 1.9. Gridded monthly meteorological data from 2002-2021 with a cell size of ~ 4 km were obtained from the TerraClimate dataset (Abatzoglou et al., 2018). They were summarized to compute the annual sum of total precipitation along with annual means of maximum air temperature and vapor pressure deficit.

2.3 Analysis

The mean annual number of active fires was computed for each 0.05 degree cell and used to map the spatial patterns of active fire frequency across the study area. For temporal analysis, all variables were further aggregated to 0.25 degree cells. The larger cells were only used in the analysis if they contained at least 13 of the smaller cells 0.05 degree cells (> 50% of the total cell area). Fire and weather variables were aggregated as means, and annual percent forest loss was calculated as the total number of forest loss pixels for a given year divided by the total number of forest pixels in 2000.

Trend analysis was conducted for all variables (active fires, forest loss, precipitation, maximum temperature, and vapor pressure deficit) using Mann-Kendall tests. Sen's slope values were also computed to describe the direction and magnitude of the trends. Annual fire anomalies were evaluated using Z-scores computed for each pixel as

$$Z_i = \frac{(AF_i - \overline{AF})}{s_{AF}}$$

where AF_i was the active fire count in year i, $\overline{AF}$ was the mean active fire count from 2003-2021, and s_{AF} was the standard deviation of active fire counts from 2003-2021.

The temporal patterns of fires in each cell were assessed using Spearman's rank correlations of annual active fire counts with annual summaries of the forest loss and meteorological variables for each grid cell. These correlations were calculated using active fire counts with environmental predictors from the same year and with lagged environmental predictors from the preceding year. Spatial patterns of fire trends were assessed using Spearman's rank correlations of Sen's slope values from the fire trends with (1) 2003-2021 means of forest loss and the meteorological variables, and (2) Sen's slope values from the trends of forest loss and the meterological variables. All statistical tests were conducted at an alpha-level of 0.05.

3 Results

Active fire counts were highest in areas near the edges and outside of the forest ecoregions (Figure 2a). In West Africa, lower levels of fire activity (> 0 and <= 4 active fires per 0.05 degree cell per year) were common throughout most of the region with concentrations of higher fire activity (> 4 active fires per 0.05 degree cell per year) in the westernmost parts of the Western Guinean Lowland Forests. In Central Africa, there were large expanses where no active fires were detected between 2003-2021. However, there were also many areas with low levels of active fires similar to West Africa, as well as clusters of higher fire activity, particularly in the Central and Northeastern Congolian Lowland Forests.

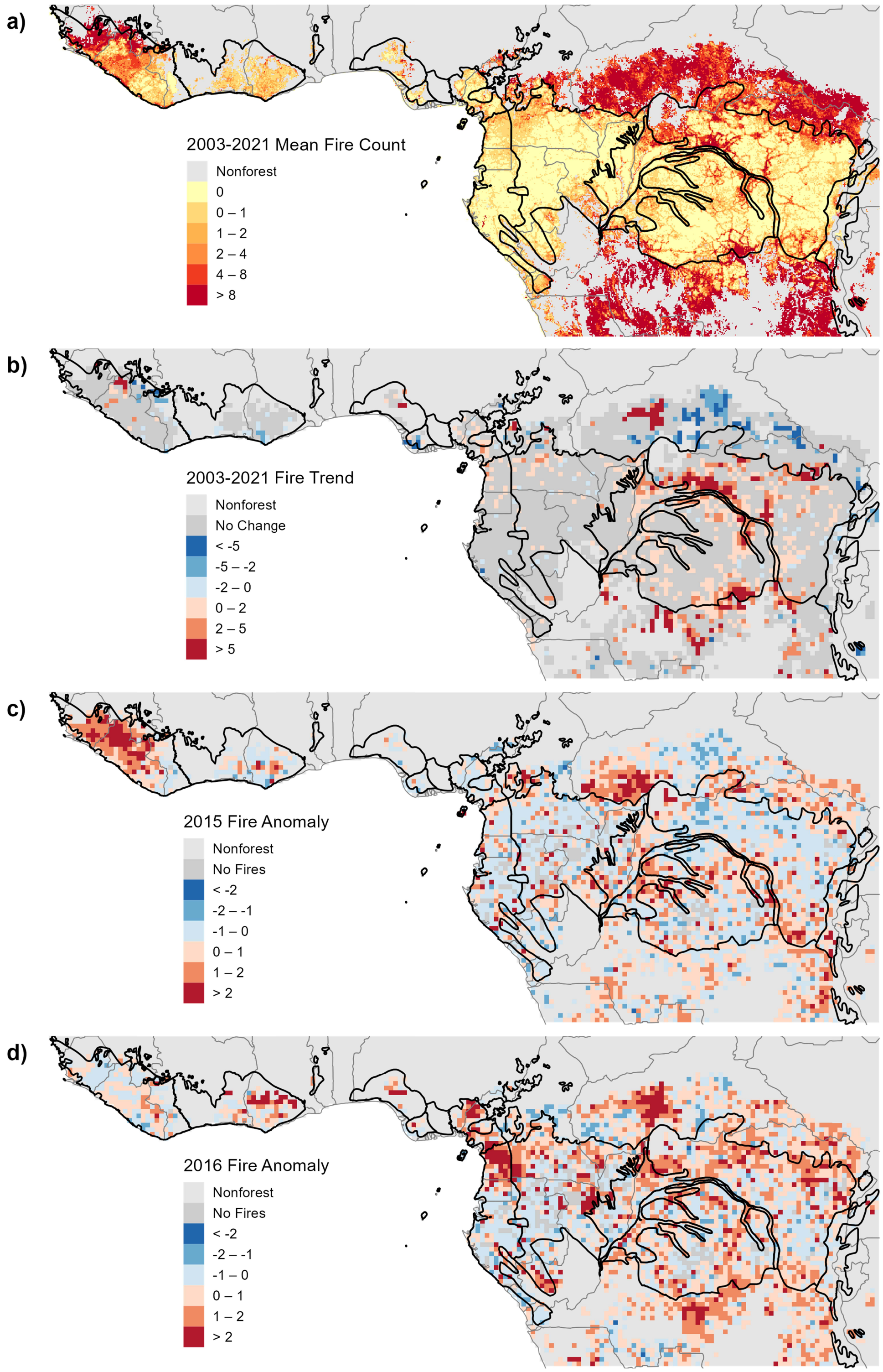

Figure 2. MODIS active fire patterns in West and Central Africa. a) Mean annual fire density per 0.05 degree cell. b) Trends from 2003-2021 in the number of fires per year per 0.25 degree cell based on Sen's slope. Only statistically significant trends at an alpha-level of 0.05 are displayed. Anomalies for c) 2015, and d) 2016 displayed as Z-scores for each 0.25 degree cell based on the mean and standard deviation of active fires from 2003-2021.

Positive fire trends were primarily concentrated in the Congo basin (Figure 2b). In the Central Congolian Lowland Forest and the Eastern and Western Congolian Swamp Forests, active fire increases were nearly linear, with densities of active fires approximately doubling between 2003-2021 (Figure 3c, e, i). In the Cross-Sanaga-Bioko Coastal Forests and the Northeastern and Northwestern Congolian Lowland Forests, the rate of increase was initially slower but increased after after 2012 (Figure 3d, g-h). In the Eastern Guinean and Western Guinean Lowland Forests, fire densities increased through 2016 and 2015 but declined thereafter (Figure 3f, j).

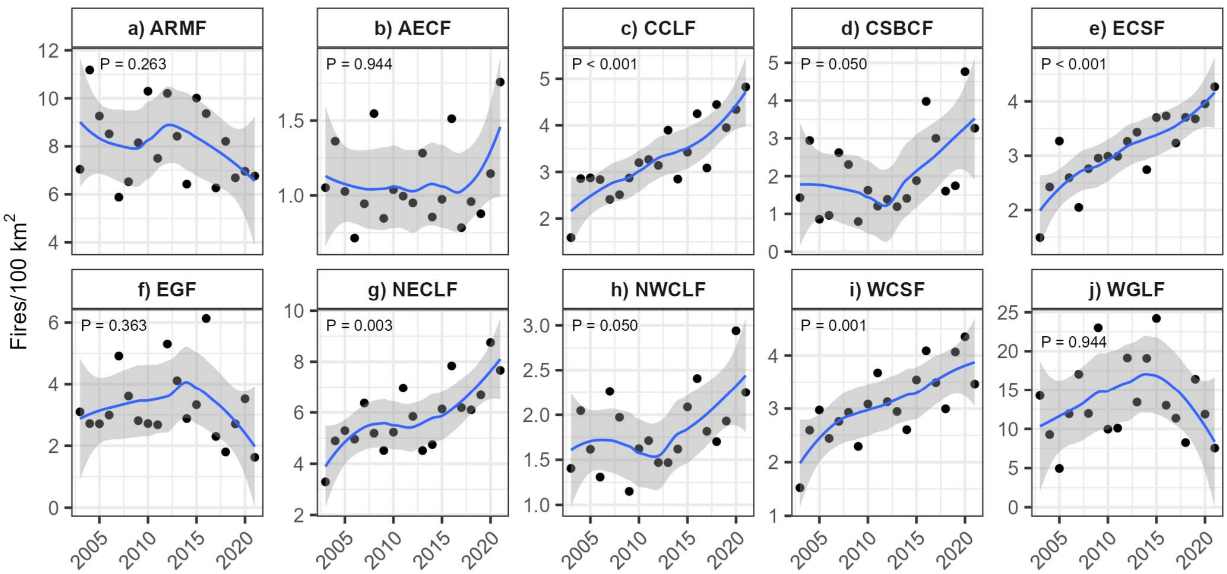

Figure 3. Trends of annual MODIS active fire density for ten tropical and subtropical moist broadleaf forest ecoregions in West and Central Africa. Smoothed lines and 95% confidence intervals are generated using local polynomial regression. P-values are from Mann-Kendall trend tests. Ecoregion abbreviations are defined and boundaries are mapped in Figure 1.

There were higher-than-expected areas of positive fire anomalies throughout the region in 2015 and 2016, when 10% and 14% of the study area had Z-scores higher than the 95th percentile (Figure 2c, d, Figure S1). These percentages were higher than in any of the previous 12 years from 2013-2014. There were also widespread positive fire anomalies in 2020 and 2021, when 17% and 14% of the study area had Z-scores higher than the 95th percentile (Figure S1, S2).

There were small areas with increasing trends of forest loss throughout the study area, along with largers ares of decreasing precipitation in the western Congo Basin and increasing maximum temperature and vapor pressure deficit throughout the study area (Figure S3). Temporal variation in active fires had positive correlations with temporal variation in temperature and vapor pressure deficit in the locations where positive fire trends were detected (Figure 4c-d). There were smaller areas of negative correlations with precipitation, primarily in the western Congo Basin (Figure 4b). Only a few locations exhibited positive correlations with forest loss (Figure 4a). These patterns of temporal correlation were very similar when they were assessed with a lag of one year between the meteorological and forest loss variables and the active fire observations (Figure S4).

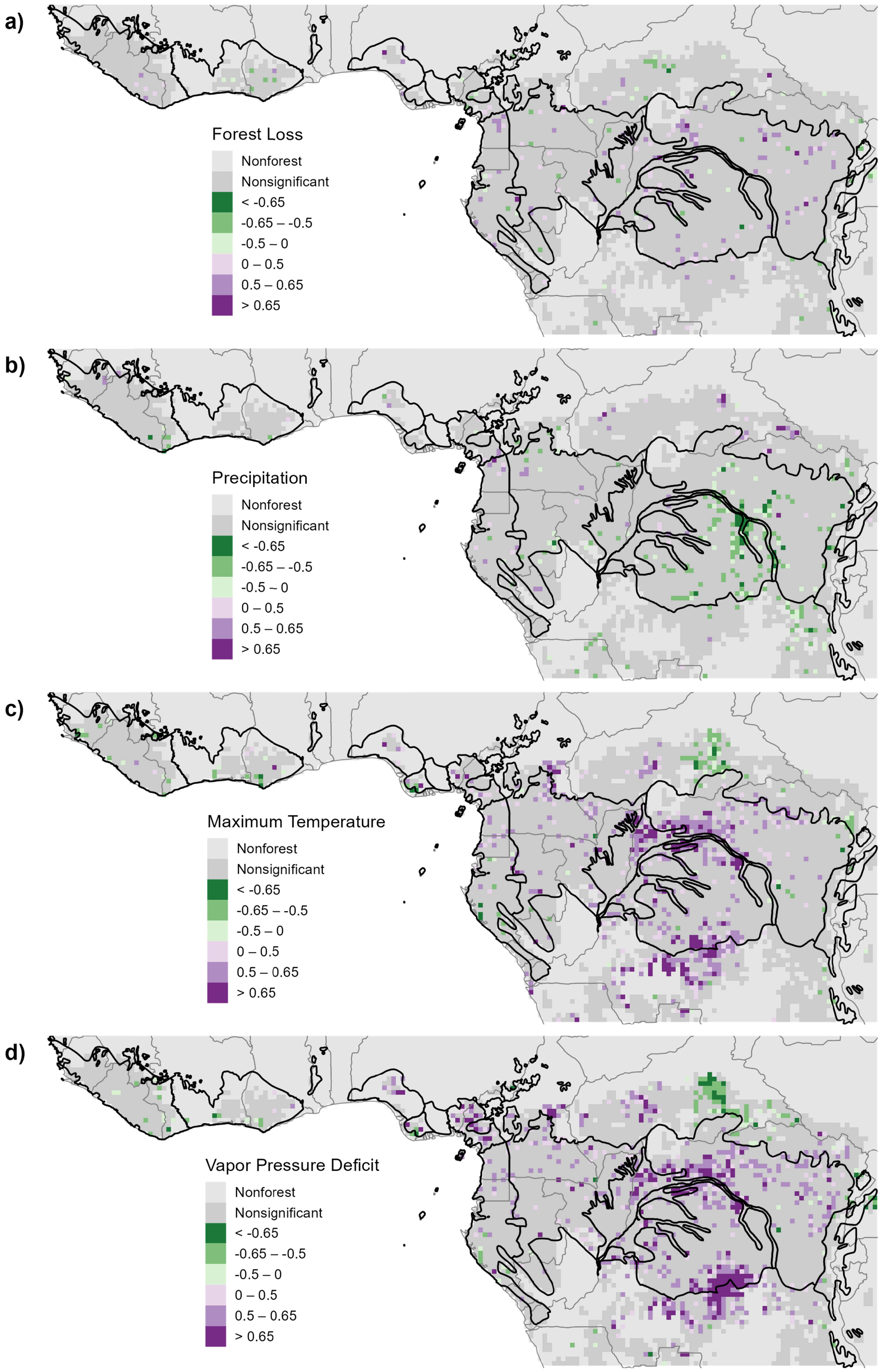

Figure 4. Spearman rank correlations between annual summaries of environmental variables and MODIS active fires for each 0.25 degree cell in the same year. a) Forest loss. b) Precipitation. c) Maximum temperature. d) Vapor pressure deficit. Only correlations that are statistically significant at an alpha-level of 0.05 are displayed.

In the Congolian Forest Ecoregions positive fire trends occurred in locations where there were higher rates of forest loss (Figure 5c, e, g-i). These spatial correlations with forest loss were generally stronger than correlations with meteorological variables. However, in the Western Guinean Lowland Forests fire trends had no spatial correlation with forest loss (Figure 5j), and in the Albertine Rift Montane Forests and Eastern Guinean Forests, fire trends had negative correlations with forest loss (Figure 5b, f). The results were similar when spatial correlations with environmental trends were assessed (Figure S5). There were consistent positive correlations with forest loss trends in the Congolian Forest Ecoregions, whereas the meteorological correlations were generally weaker and more variable.

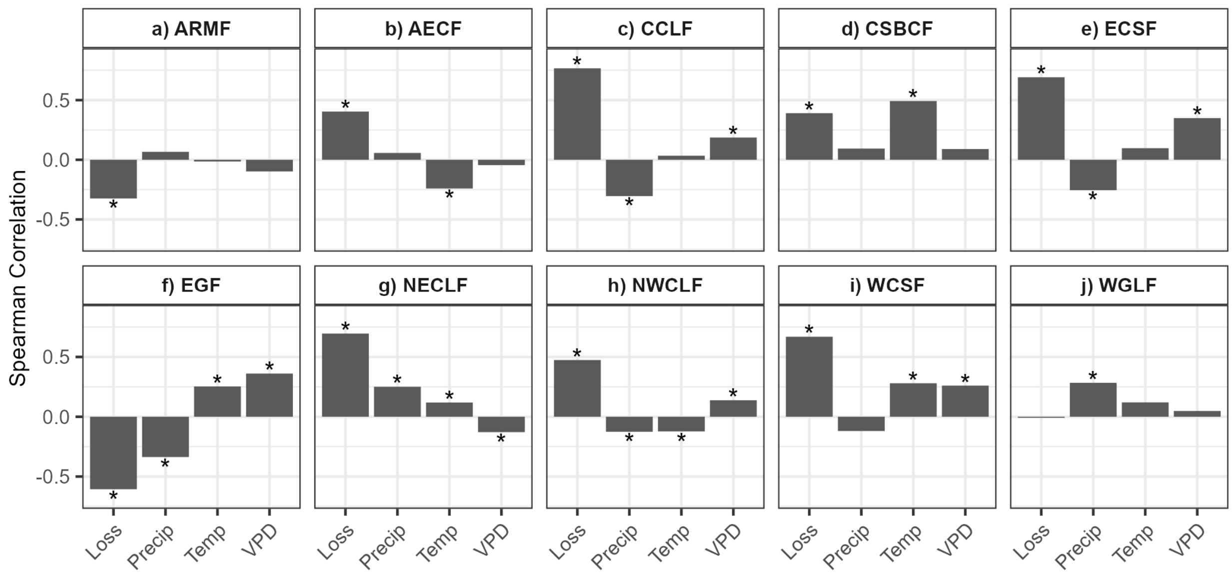

Figure 5. Spearman rank correlations between mean values of environmental variables from 2003-2021 and MODIS active fires trends calculated across 0.25 degree cells within ten tropical and subtropical moist broadleaf forest ecoregions in West and Central Africa. Stars indicate correlations that are statistically significant at an alpha-level of 0.05. Ecoregion abbreviations are defined and boundaries are mapped in Figure 1.

4 Discussion

We identified increasing trends in active fire detections in multiple tropical forest ecoregions, with hot spots concentrated in several locations within the Congo Basin. These positive trends occurred in places where forest loss rates were high and increasing over time, but the year-to-year variation in fires was not synchronized with fluctuations in forest loss. Instead, the temporal patterns of active fire detections were correlated with increasing trends of temperature and vapor pressure deficit. In this context, forest loss serves as a general indicator of human activity, which generates ignitions from burning for land clearing and agriculture. Forest loss also fragments the remaining forests, which increases the potential for fire encroachment by altering understory microclimate and fuels (Zhao et al., 2021). However, the lack of a strong temporal correlation between fire and forest loss suggests that these are long-term cumulative effects rather than immediate impacts of deforestation. The year-to-year variation in active fires is instead primarily associated with fluctuations in temperature and atmospheric moisture. Thus, high levels of human land use provide ignitions and create fragmented landscapes that are more conducive to burning, while increases in temperature and vapor pressure reduce fuel moisture and enhance the potential for fire ignition and spread (Griebel et al., 2023). These results present a sharp contrast to fire trends in African savanna ecoregions, where burned area has exhibited strong declining trends that have been attributed to climate variation and the conversion and fragmentation of fire-prone savanna vegetation (Andela et al., 2017; Jones et al., 2022; Zubkova et al., 2019).

In the future, temperatures will continue rising and droughts are projected to become more frequent in Africa because of climate change. Land use pressure will also increase because of growing populations and the accompanying demands for food and natural resources, as well as international investments in large-scale agricultural and forestry projects. As a result, the historical trends of increasing fire in the African tropical forests are likely to persist. Future strong El-Nino events will probably drive increased wildfire in African tropical forests like the anomalies we documented in 2015-2016 and the widespread burning that was reported in West Africa during the strong El-Nino events of the 1980s (Hawthorne, 1994; Hawthorne & Abu-Juam, 1995). However, the positive fire anomalies that we found in 2020-2021 also show that wildfire outbreaks can also occur during the La-Nina phase of the El Niño–Southern Oscillation, emphasizing the need for more research on the complex relationships between modes of climate variability and the risk fo wildfire in the African tropics. Many tropical forest fires burn at low severity and their immediate effects are relatively minor, but they can increase the potential for future fire ignitions and spread, generating feedback loops that gradually reduce tree cover and ultimately result in forest loss (Cochrane et al., 1999). This phenomenon has been documented in Ghana, where droughts during the 1980's initiated a cycle of fire and forest degradation that converted two entire forest reserves to fire-maintained grass and shrublands by 2000 (Dwomoh & Wimberly, 2017a). Overall, fires are likely to become an increasingly significant factor influencing forest dynamics in tropical Africa as a result of global change.

Understanding how tropical carbon sinks will respond to climate and land use changes is essential for projecting future land-atmosphere interactions and developing adaptation strategies. Recent studies based on data from long-term field plots in structurally intact forests have concluded that drought and temperature extremes during the 2015-2016 El Niño had relatively small effects on forest disturbance and carbon balance in the African tropics compared with Amazonia (Bennett et al., 2021; Hubau et al., 2020). In contrast, pantropical studies based on satellite remote sensing have concluded that the 2015-2016 El Niño resulted in persistent declines in tropical forest carbon stocks in both Africa and Amazonia (Wigneron et al., 2020; Yang et al., 2022). One reason for these different results may be that recovery in degraded forests is slower than in more structurally intact forests with multilayered canopies (Yang et al., 2022). Most research on carbon sequestration in African forests has not explicitly considered the effects of fire A study of the atmospheric CO_2 responses to El Niño in 2015 found that fire accounted for 25% of NBE in tropical Africa, although this estimate included savannas in addition to forests (Liu et al., 2017). In the tropical forest region of Ghana, fire accounted for 45% of the total disturbed area during the 2016 El Niño drought compared to less than 10% in other years (Wanyama et al., 2023). As fires become more widespread throughout the African tropics, they will gain more importance as proximal drivers of drought effects on forest biomass, particularly in degraded and fragmented forests.

There has been increasing recognition of the importance of fire as a driver of forest degradation and loss in the Amazon. Numerous recent studies have characterized fire regimes, identified their drivers, and assessed their effects on the ecosystem dynamics and biodiversity (Alencar et al., 2015; Barni et al., 2021; da Silva et al., 2018; Feng et al., 2021). In contrast, relatively little research has been published on forest fires in the African tropics (Juárez-Orozco et al., 2017). Most studies to date have either made general comparisons between forest and non-forest regions (Dwomoh & Wimberly, 2017b; Zubkova et al., 2019) or focused on more localized case studies (Dwomoh et al., 2019; Shapiro et al., 2021; Verhegghen et al., 2016). More fire research is urgently needed in tropical Africa to improve our understanding of how climate and land use change will affect forest ecosystem services, including carbon storage as well as biodiversity and the provisioning of resources for local communities. Where the risk of wildfire is increasing, there will be opportunities for climate change mitigation through wildfire prevention and forest restoration. These efforts will need to be locally tailored to fit the diverse range of ecological settings and social contexts across the African continent. In addition, broader-scale tools such as fire danger rating and forecasting systems would provide valuable information to support local responses.

5 Conclusions

Satellite-detected active fires have increased from 2003-2021 in many forested ecoregions in tropical Africa. These results contrast sharply with the drier African woodlands and savannas, where fires have been steadily decreasing. Forest fires are increasing in locations where rapid forest loss is occuring, and the trends are synchronized with increasing temperature and atmospheric drying in these locations. Fires are likely to continue increasing as temperatures become hotter and human populations continue to grow and expand. As fires become more widespread throughout African tropical forests, they will have negative impacts on carbon storage as well as biodiversity and human livelihoods derived from forest resources. To date there has been limited research on fire in African forests, and more work is needed to understand how ENSO and other climate modes influence regional patterns of fire risk; assess the impacts of increasing fire on carbon dynamics, biodiversity, and forest resources; and develop more effective strategies for predicting fire danger and preventing destructive wildfires.

Acknowledgments

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Open Research

All data used in this research are publicly accessible. Archived MODIS active fire data were obtained from the NASA Fire Information for Resource Management System (https://firms.modaps.eosdis.nasa.gov/download/). Monthly TerraClimate weather data were obtained from Climatology Lab (https://www.climatologylab.org/terraclimate.html). Forest loss data were obtained from the Global Forest Change website (https://glad.earthengine.app/view/global-forest-change). Data processing and analysis were carried out using the R software environment for statistical computing and graphics (https://www.r-project.org/).

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