Advanced Journal of Environmental Sciences
Volume.16, Number 6; June-2025;
ISSN: 2837-3928 | Impact Factor: 9.38
https://zapjournals.com/Journals/index.php/ajes
Published By: Zendo Academic Publishing

ASSESSING WILDFIRE OCCURRENCE IN WEST AFRICA WITH ATMOSPHERIC CO_2 REMOVAL

[1*]Uzoma E.K., [2]Otunla T. A., [2]Nymphas E. F., [2]Ogunsola O. E. and [2]Adeniyi M. O.
Email: [1]uzomaechefulachik@gmail.com, [2]biodunotunla@gmail.com, [2]efnda@yahoo.co.uk, [2]seyiogunsola22@gmail.com, [2]mojisolaadeniyi@yahoo.com
Phone: +2347033814023, +2348033579081
ORCID: https://orcid.org/0000-0003-2662-1481

Article Info
Keywords: West Africa, Temperature, Wildfire, Carbon Dioxide Removal, Lebanese Index, Low Risk
DOI
10.5281/zenodo.15623178

Abstract
The increase in wildfire occurrence is one of the consequences of the recent global temperature rise. Understanding wildfire occurrence in West Africa under atmospheric carbon dioxide removal is significant because of its implications on climate systems, ecosystems, agriculture, and socioeconomic development. This study projected the impacts of atmospheric carbon dioxide removal on fire occurrence in West Africa by analyzing the CNRM ESM1 C1 model output for the Carbon Dioxide Removal Model Inter-comparison Project (CDRMIP). Four climatological periods–1990–2019 (reference period), 2040 – 2069, 2070–2099 and 2100-2129 were analyzed using four fire indices. The periods 2040–2069, 2070–2099, and 2100–2129 have 42%, 45.9%, and 49.4% of "No Fire" category among other categories, respectively, with the Lebanese Index. With Mark 4 Grassland Fire Danger Index, a low category of fire risk is also predominant at 95.6%, 96.4%, and 66.1% for 2040–2069, 2070–2099, and 2100–2129, respectively. None of the indices projected a case of high, very high, or extreme risk in any period. "Low risk" category is predominant with all indices, particularly in Cote D'Ivoire, Ghana, Burkina Faso, Togo, Benin, and Nigeria. The low-risk category for fire occurrence during carbon dioxide removal in West Africa suggests a favorable outcome for the region's ecosystems, agriculture, and communities. The study highlights the potential benefits of CDR beyond carbon removal, such as enhanced resilience, sustained productivity, and reduced vulnerability to climate-induced hazards like wildfires.

[1] Department of Physics, Hezekiah University, Umudi, Nkwerre, Nigeria
[2] Department of Physics, University of Ibadan, Ibadan, Nigeria

1. Introduction

The impacts of climate change around the world are taking a toll on various aspects of human existence, particularly wildfire occurrence. These impacts have the potential to worsen in the future unless something is done to reduce them. This will include reducing greenhouse gas emissions and its removal from the atmosphere (Climate Reality Project, 2023). The main greenhouse gases emitted from biomass burning are carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4) (Vernooij et al., 2021; Kauffman et al., 2016). Among these gases, CO_2 is the major gas produced from plant respiration, decomposition, and rapid oxidation during fires (Kauffman et al., 2016). Climate change has been a key factor in increasing the risk and extent of wildfires. Areas burned by wildfires are exacerbated by a warm and dry climate (Abatzoglou and Kolden, 2013). Wildfire risk depends on many factors, including temperature, soil moisture, and the presence of trees, shrubs, and other potential fuels. These factors have strong direct or indirect ties to climate variability and climate change. Climate change enhances the drying of organic matter in forests, that is, the material that burns and spreads wildfire (Centre for Climate and Energy Solution, 2023).

Anthropogenic activities release greenhouse gases into the atmosphere, and by the greenhouse effect, the concentration of surface longwave radiations, which have a warming effect on the planet, is increased, and the Earth's surface temperature rises (Maslin, 2008). The increase in the surface temperature (warming) is due to the rising atmospheric carbon dioxide concentration (Zafar *et al.*, 2018). Hotter temperatures and droughts are some of the effects of climate change, and wildfires start more easily and spread more rapidly when conditions are hotter (United Nations, 2023). Wildfires will become more frequent, more intense, and more enduring as global temperatures continue to rise in response to human emissions of CO_2 from the combustion of fossil fuels (UNEP, 2022). Fire occurs as a function of suitable environmental conditions—the co-occurrence of adequate fuels, conditions conducive to combustion and spread, and ignition agents. Simply put, more frequent or more numerous consecutive days of hot, dry, and windy weather translate into more and often larger wildfires when these conditions coincide with the presence of ignitions (Jones et al., 2022).

Even in years without extreme wildfire activity, the financial burden of fire suppression is considerable in some regions (Jones et al., 2022). For instance, Canada spends approximately US$500 million annually, whereas the United States allocates between US$1–2 billion each year on fire suppression efforts (Hope et al., 2016; Jolly et al., 2015; National Interagency Fire Center, 2020; Stocks and Martell, 2016; Tymstra et al., 2020). Beyond the immediate damage caused by wildfires, smoke exposure significantly impacts public health, contributing to more than 300,000 premature deaths annually—especially in tropical areas (Johnston et al., 2012; Balmes, 2020; Reid et al., 2016). In Australia, for example, the 2019/2020 wildfire season led to an estimated US$1.5 billion in healthcare costs related to smoke-induced respiratory problems (Johnston et al., 2021). In addition, the fire affected over 30% of the habitat of 70 vertebrate species, including 21 species classified as endangered (Ward et al., 2020). Fire acts as a major ecological disturbance that can trigger shifts from forested to non-forested landscapes, particularly where climatic changes are misaligned with existing vegetation, thereby affecting biodiversity, carbon sequestration, and other ecosystem functions (Burrell et al., 2020, 2021; He et al., 2019; Hirota et al., 2011; Staver et al., 2011).

Patterns of lightning and human land use can substantially influence the occurrence of fire (Parisien and Moritz, 2009). Warmer temperatures are increasing the amount of moisture in the atmosphere, which can lead to more thunderstorms. Lightning is a major cause of wildfires, and an increase in lightning strikes may contribute to an increase in the number of wildfires (Climate Reality Project, 2023). The occurrence of natural wildfires around the world has been associated with dry lightning (Moris *et al.*, 2020; Rodríguez-Pérez *et al.*, 2020; Nampak *et al.*, 2021). Lightning-caused fires are related to dry thunderstorm events, that is, when the occurrence of lightning is accompanied by little or no precipitation to suppress or extinguish ignitions and are referred to as “dry lightning” (Nauslar *et al.,* 2018). Owing to the regular and widespread occurrence of wildland fires, Africa is often referred to as the “fire continent”, especially the Southern and Eastern Africa, where the Savannah biome is a major plant community. The continent is highly prone to lightning storms and has a fire climate with both dry and wet periods, where fires can burn the fuels produced and accumulated during the wet, rainy period (Global Forest Resources Assessment 2000). Tutin *et al*. (1996) reported a large forest tree in Lope Reserve, Gabon, burned due to fires ignited by lightning. Lightning-caused fires represent 16% of all wildfires within the Continental United States for the period of 1992–2013 and account for 56% of the total acreage burned (Balch *et al.*, 2017). Fires in African tropical forests are likely to continue increasing as temperatures become hotter and human populations grow and expand. Such increases will have negative impacts on carbon storage, biodiversity, and human livelihoods derived from forest resources (Wimberly et al., 2024).

Smoke particles emitted from fires are sources of atmospheric aerosols (Andreae and Merlet, 2001). They can impact shortwave radiation by scattering and absorbing solar radiation, a mechanism known as direct radiative forcing (Charlson *et al.,* 1992). Clouds play a major role in atmospheric radiation transfer. As Cloud Condensation Nuclei (CCNs), smoke particles can impact solar radiation by modifying the formation, structure, and lifetime of clouds through a mechanism called indirect radiative forcing (Twomey *et al.*, 1984; Kaufman and Tanré, 1994). According to Hansen *et al.* (1997), aerosol radiative forcing changes the atmospheric structure, circulation, energy, and water exchanges on the ground surface, affecting atmospheric water vapor and clouds, which eventually affects radiation. This mechanism is known as semi-direct aerosol radiative forcing. The more the fires, the more the tendency for the GHG concentration (which includes carbon dioxide, methane, and nitrous oxide) in the atmosphere (Koppmann *et al.*, 2005) and the aerosol particles (Grégoire *et al.*, 2013).

A fire without control causes great harm, ranging from destruction of property, forest cover, agriculture produce to the worst of all, loss of human life (Kabo-Bah et al., 2016b). Using data from 2003 to 2012, it is estimated that about 67 million hectares of forest land are lost annually from burning, with most of these located in Africa and South America (van Lierop et al, 2015). The proportion of tree cover and tree growth rates alter the Earth’s carbon cycle. These areas are affected by fire regimes, especially in mesic savannas with precipitation exceeding 650 mm per year (Bond, 2008). Wildfires occurrences result in significant negative impacts on natural resources (Loehman *et al.,* 2014 and Levine, 1994). Their negative impacts are manifested in the form of organic matter loss, soil leaching and erosion, intense evaporation leading to soil moisture depletion, severe environmental effects such as loss of natural habitat and cultural heritage, deforestation and biodiversity loss, loss of human lives and pollution of water resources (Gomes, 2006). Furthermore, it encourages the distortion of air quality with the release of large quantity of GHGs (Loehman *et al.*, 2014 and Levine, 1994). African Savannas are considered among the most Earth’s fire-prone regions (Giglio *et al.,* 2010). Grégoire *et al.* (2013) observed that, out of the global estimate of the areas burned on an annual basis, sixty-four percent of them are traceable to the African Savanna. Due to the high emission of greenhouse gases (GHGs) because of Savanna fires, vegetation cover can be altered (Roberts *et al.,* 2009).

There are reported cases of wildfires in parts of West Africa dotted across the region, mainly resulting in loss to agricultural lands and forestry (Danthu et al., 2003; Joubert et al., 2012; Kennedy et al., 1994; Kraaij and Ward, 2006; Reddad et al., 2013). The lack of capacity in predicting and forecasting fire outbreaks in the region is costly, leading to loss of life and property (Kabo-Bah et al., 2016b). It is already envisaged that with the adverse effects of climate change, temperatures are likely to increase while rainfall may decrease in parts of West Africa (Kabo-

Bah et al., 2016a; Roudier et al., 2011; Sultan et al., 2013); this would obviously accelerate the frequency of wildfire outbreaks during the dry seasons (Kabo-Bah et al., 2016b). In West Africa, during the severe drought of 1982/1983, wildfires ravaged the region to an extent that approximately 50 % of the region's vegetative cover was destroyed (FAO, 2007). In the aftermath, soil fertility has since been reduced due to the destruction of soil organic matter; forest areas have seen a change in the species composition.

Due to the availability of combustible grassy fuel as a result of long periods of drought, the spread of fire is more predominant in the central Savanna region, placing the region at a high risk of fire occurrences and hence making African Savannas major contributors to global climate change. Fires in West African Savannas can burn intensely due to the lower moisture content and continuous spatial distribution of biomass fuel, causing greater carbon emissions with 1.61 ± 0.13 t C ha^{-1} in grass areas and 1.01 ± 0.13 t C ha^{-1} in shrub areas (Yaro et al., 2024). NASA (2009) identified locations such as Cote D'Ivoire, Burkina Faso, Benin, Togo, Ghana, and Nigeria as wildfire-prone areas within the West African Savanna region. Large biomass land size and the strict two seasons (wet and dry seasons) are some of the reasons for fire occurrence in these locations. The wet season supports vegetation growth, which lowers surface and air temperatures by providing shade and cooling through evapotranspiration, whereas the dry season generates conditions for vegetation fire outbreaks (Tedim *et al.*, 2018; US EPA, 2023). According to Rao *et al.* (2023), dense vegetation, dry litter, dry vegetation, high winds, and warm air all contribute to high fire likelihood.

To determine the dynamics of the West African landscape, wildfires are important factors to be considered (Kull and Laris, 2009; Shlisky *et al.*, 2009). Devineau *et al.* (2010) studied fire regimes in Burkina Faso and established a relationship between fire regimes and vegetation patterns. According to Caillault *et al.* (2011), the fire regime follows the vegetation pattern, which was determined to be a function of topography and agricultural density in Burkina Faso. Laris (2013) added that the Savanna fire regime is determined by factors such as burning activities by humans, the type of vegetation cover, and the landscape pattern.

Among these literatures, none considered the relationship between wildfire occurrence and carbon dioxide removal in West Africa. Therefore, this study considers this relationship in West Africa by analyzing the CNRM-ESM1-C1 experiment for Carbon Dioxide Removal Model Inter-comparison Project (CDRMIP) simulation output. This section provides simulations to investigate the effects of carbon dioxide removal (CDR) on the Earth system. The data are widely used in climate studies, including projections of environmental impacts and policy-driven simulations for mitigation and adaptation strategies.

2. Data

2.1 Model simulation

The data used are near-surface temperature, relative humidity, wind speed at a height of 10 m, and soil temperature, which are the Centre National de Recherches Meteorologiques, Earth System Model-simulation output of the C1 experiment. The model output from the C1 experiment provides monthly data for the Carbon Dioxide Removal Model Intercomparison Project (CDRMIP). In this experiment, atmospheric CO_2 levels are reduced by 1% annually until they return to preindustrial levels, as described by Keller et al. (2018). The experiment explores the climate system's ability to revert to its initial state by building upon the 1% per year CO_2 increase scenario (1pctCO2) introduced by Eyring et al. (2016). The 1pctCO_2 experiment originates from the DECK preindustrial control experiment, which represents a stable climate state as of the year 1850. Starting from this baseline—when global mean CO_2 concentration was 284.7 ppm—CO_2 levels were increased by 1% per year, with CO_2 being the only external forcing. This increase continued until the concentration quadrupled to 1138.8 ppm. At that peak, CO_2 removal began at the same rate (1% annually) and continued until levels returned to the preindustrial value of 284.7 ppm. All other forcings remained constant throughout this phase. Once CO_2 levels returned to 284.7 ppm, they were held steady for at least 60 years to observe long-term climate responses (Keller et al., 2018). The CDRMIP datasets are available on the ESGF (https://esgf-node.llnl.gov/projects/cmip6/) and are freely available to download. The coordinates for the region of interest in this work, West Africa, are longitude (20°W – 20°E) and latitude (0°N – 25°N).

2.2 Study area

West Africa has a varied climate, with the northern region being characterized by a semi-arid tropical climate, while the southern regions experience a moist tropical climate. Currently, this region is largely composed of perennial grasses interspersed with shrubs and trees, and it receives an average annual precipitation ranging from 150 to 2500 millimeters (Scholes and Archer, 1997). According to the categorization established by the UN, the region known as West Africa includes 16 nations and covers an extensive area exceeding 6 million square kilometers (Figure 3.1). The region's coordinate lies between latitude (0°N, 25°N) and longitude (20°W, 20°E). The definition of the eastern frontier is subject to varying interpretations; however, it is commonly described as extending from Mount Cameroon to Lake Chad. The terrain across most of West Africa is relatively flat, with altitudes generally not exceeding 300 m above sea level. Nevertheless, certain areas in the southern portion of the

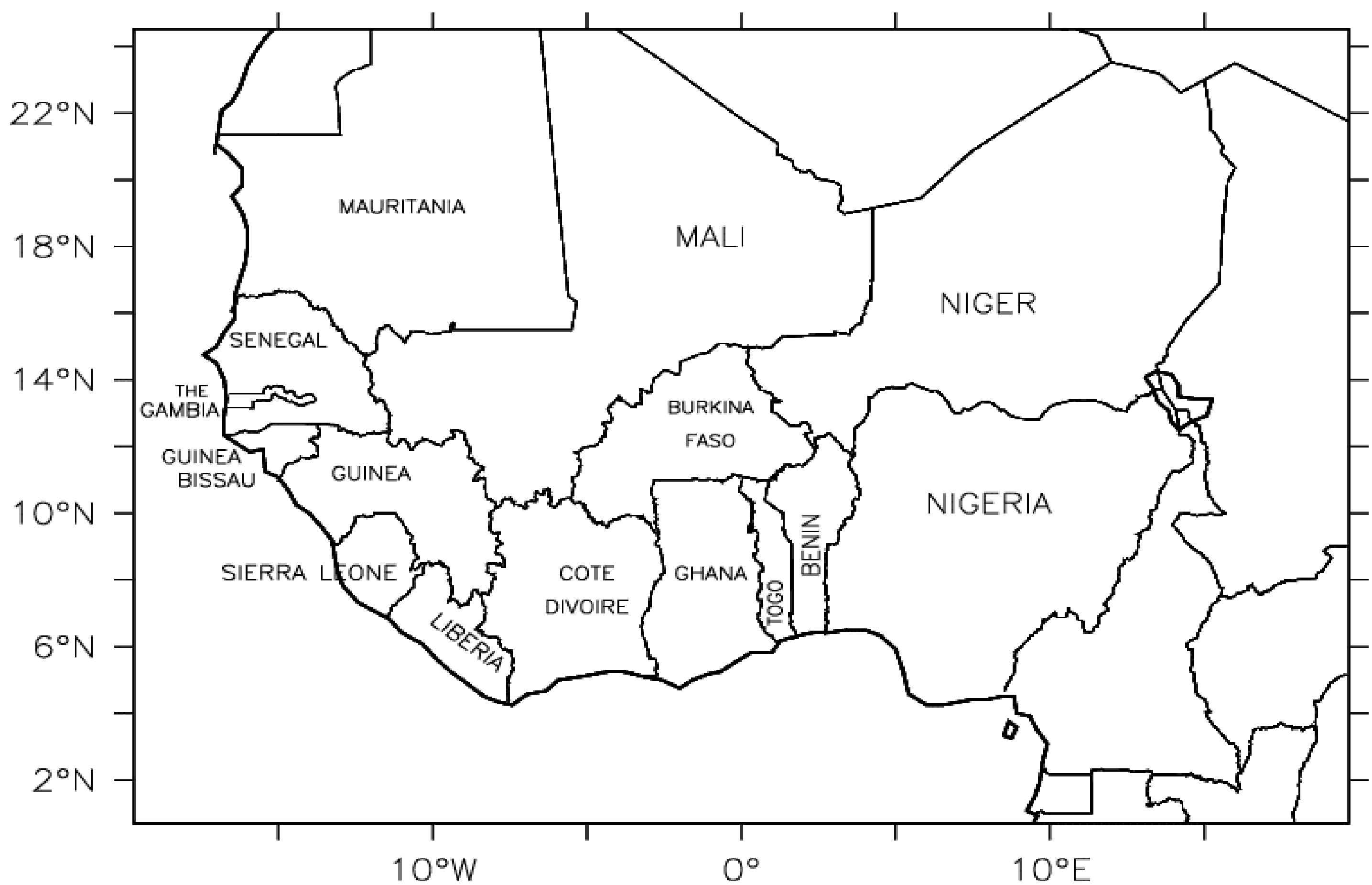

Fig. 1 Map of the Study Area

3. Methodology

3.1 Analysis of data

The output of the CNRM-ESM1-C1 experiment model over West Africa was extracted from the global output. The model's performance was evaluated using the ensemble mean of seven available model outputs (Uzoma *et al.,* 2023). The data were divided into three climatological periods: 2040–2069, 2070–2099, and 2100–2129, with 1990–2019 as the reference period. Each of the four indices—the Lebanese index (LI), the Forest Fire Danger Index (FFDI), the Mark 4 Grassland Fire Danger Index (GFDI4), and the Angstrom index (AI), was used to estimate the index value per period. Removal of carbon dioxide may lead to altered climate patterns, such as decreased temperature, increased precipitation, or shifts in humidity. These indices allow for evaluation of how such changes affect wildfire risk. LI provides insights into fire risk based on dryness and vegetation conditions. FFDI combines meteorological factors (temperature, wind speed, and humidity) with fuel conditions to assess fire danger. GFDI4 focuses on grassland fire dynamics, critical in savanna regions. AI accounts for temperature and relative humidity, offering a simplified yet valuable metric for fire danger. West Africa's diverse ecosystems (savannas, forests, and grasslands) have varying wildfire dynamics. These indices help identify regions where carbon dioxide removal-induced climatic changes might lower or increase fire risk. They also help in predicting shifts in fire regimes, such as from frequent small fires to less frequent but more intense fires. Fire-prone ecosystems such as grassland and savanna may exhibit changes in fuel load and combustibility due to CDR impacts. Indices like GFDI4 are tailored to grassland conditions, making them suitable for understanding changes in fire dynamics in savanna ecosystems. FFDI and AI provide broader applicability for mixed landscapes, such as transitional zones between forests and grasslands. The index results were categorized according to each index's potential scale, and the percentage of occurrence of each index category was plotted in a bar chart (Fig. 2). Figs. 3-6 are plots of the indices from which locations with higher fire index values and likely prone to fire occurrences are ascertained. In Fig. 7, the difference between a projected period and the reference period (projected period minus the reference period) is plotted using the Lebanese index, while the significant level of the difference is evaluated using student's t-test at $\alpha = 0.05$.

3.1.1 Lebanese Index

The Lebanese index is a simplified model fit for the fire index analysis of developing countries due to its affordability (Hamadeh *et al.,* 2017). Three weather parameters are usually engaged in the index – Temperature, Dew point and soil temperature, considering the strong statistical relationship that exists among the parameters. The equation is given below:

$$I = 1.18T + 1.07S + D \quad (1)$$

Where; I is the fire danger index, D is the dew point (°C), T is the air temperature (°C), and S is the soil temperature (°C). The dew point temperature can be calculated using Equations 2 and 3 according to Snyder *et al.,* (1984).

$$B = \frac{ln\left(\frac{RH}{100}\right) + \frac{17.27*T}{237.3+T}}{17.27} \quad (2)$$

$$D = \frac{237.3*B}{1-B} \quad (3)$$

Where; T is the air temperature (°C), RH is the relative humidity (%), B is an intermediate value (no unit), and D is the dew point (°C). The range of Lebanese index risk is shown in Table 1.

Table 1: Standard values for the Lebanese index (Snyder *et al.,* 1984)

Index	*Fire Risk*
0<I<15	*No Fire*
15<I<30	*Low Fire*
30<I<45	*Medium Risk*
45<I<60	*High Risk*
I>60	*Extreme High Risk*

3.1.2 Forest fire danger index

FFDI has been used to classify fire danger schemes in Australia. There are teleconnections, e.g., El Niño, Indian Ocean Dipole, that affect both Australia and West Africa although they operate indirectly and differently. The El Nina Southern Oscillation may reduce rainfall in parts of West Africa and increase fire risk, similar to Australia. FFDI is expressed according to McArthur (1966) as follows:

$$FFDI = 2exp^{(-0.45+0.987\ln(DF)+0.0338T-0.0345H+0.0234U)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where; T is the air temperature (°C), H is the relative humidity (%), U is the wind speed at 10m height (km/h), and DF is the drought factor used as 10 for convenience.

Table 2: Fire Danger Classification Scheme (McArthur, 1966)

Fire Risk Classification	*Index*
Low	*0–5*
Moderate	*5–12*
High	*12–24*
Very high	*24–50*
Extreme	*50–100*

3.1.3 Mark 4 Grassland Fire Danger Index (GFDI4)

This index is used to assess fire weather relevant to grasslands. According to Purton (1982), the index expression is given as

$$GFDI4 = exp^{(-1.523+1.027\ln(Q)-0.009432(100-C)^{1.536}+0.02764T-0.2205\sqrt{H}+0.6422\sqrt{U})} \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where; T, H, and U are the same as in equation (4). Q is the quantity of fuel tonnes per hectare (t/ha) (4.5 t/ha) and C is the degree of grass curing, ranging from 0% to 100% and taken to be 100% for convenience. Table 2 is also used to classify the Mark 4 grassland fire danger index.

3.1.4 Angstrom index

The Angstrom index is used to predict forest fires before their occurrence (Skvarenina *et al.*, 2003). This involves the usage of only relative humidity and air temperature and is thus expressed as follows:

$$I = \frac{H}{20} + \frac{27-T}{10} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where; H is the relative humidity (%) and T is the air temperature (°C). Its values are high in times of low danger/flammability and low in times of high danger/flammability (Schunk *et al.*, 2013).

Table 3: Angstrom Index Fire Potential Scale

Fire Risk Classification	*Index*
Fire occurrence unlikely	*Index > 4*
Fire conditions unfavorable	*4 > index > 2.5*
Fire conditions favorable	*2.5 > index > 2.0*
Fire occurrence very likely	*Index < 2*

4. Results and Discussions

The analyses show that fire potential using the Lebanese Index is predominantly in the “No Fire” and ”Low Risk” categories throughout the periods in West Africa. The periods 2040–2069, 2070–2099, and 2100–2129 have 42%, 45.9%, and 49.4% of “No Fire” category among other categories, respectively. The percentage of “Low Risk” category is 57%, 53.6%, and 50.6% for 2040–2069, 2070–2099, and 2100–2129, respectively (Fig. 2a). Among the other categories, the Low and Moderate risk categories dominated the forest fire danger index for each period (Fig. 2b). With the Mark 4 Grassland Fire Danger Index, the low-level category of fire risk is also predominant at 95.6%, 96.4%, and 66.1% for 2040–2069, 2070–2099, and 2100–2129, respectively (Fig. 2c). There are no cases of high, very high, or extreme risk categories projected by any of these indices in any of the periods (Fig. 2). The dominance of Low categories indicates that the region will experience favorable weather conditions and high moisture content of grasses and other dry organic material on the ground during these periods, with carbon dioxide removal from the atmosphere. However, the low risk suggests that outdoor burning under these conditions should be performed with caution. Surface temperature reduction and low probability of fast-moving fire are expected in each period. Removal of carbon dioxide encourages reduction in warming and cooling of the surface with improved moisture content; reduces severe heat and drought and hence presents an unfavorable condition for wildfires to easily start and spread. Cooling temperature reduces the rate of evaporation, resulting in the retention of moisture by plants on the land and enhanced vegetation growth. Therefore, with a spark of fire, there will not be a quick catch and spread of fire over large areas. On the contrary, warming temperatures evaporate more moisture from soil and vegetation, drying out trees, shrubs, and grasses, and turning leaf litter and fallen branches into kindling. In times of drought, trees that are stressed by a lack of water may also become more vulnerable to insects and diseases that can weaken or kill them, creating more fuel for fires. Climate change affects wildfires by intensifying the hot, dry conditions that help them catch and spread (Environmental Defense Fund, 2023). Under the moderate risk category, marginal weather and lowered moisture content of grasses and other dry organic material on the ground are expected, with some potential for fire spread. Any outdoor burning should be carefully monitored. The lack of projection of High, Very High and Extreme risk categories in all the periods further suggests that no unfavorable weather conditions are expected since there is no high potential for fire to spread in any of the periods. The Angstrom index also shows that the predominant fire risk category is “Condition Unfavorable” in all the periods, that is, 61.7%, 69.5%, and 50.3% for 2040–2069, 2070–2099, and 2100–2129, respectively. No dangerous and critical burning conditions exist as no rapid spread of fires and erratic behaviors are expected (Fig.2d). This also means that if carbon dioxide is removed from the atmosphere, there will be possibility of not having fire-threatening or thriving conditions in the region.

Generally, the predominance of the "Low Risk" category for fire occurrence during carbon dioxide removal has significant implications across environmental, agricultural, and socioeconomic dimensions. Lower fire risks minimize ecosystem damage, preserving biodiversity in vulnerable areas of West Africa, such as forests and savannas. Lower fire occurrence means vegetation can grow undisturbed, enhancing the carbon sequestration potential and reinforcing the goals of CDR strategies. With reduced fire frequency, soil integrity, and nutrient cycles remain stable, supporting long-term ecosystem health. Low fire risk decreases the chances of agricultural land being damaged by wildfires, ensuring better yields and food security. Grasslands are less likely to experience destructive fires, providing consistent grazing opportunities for livestock, which is critical in the Sahel and savanna regions. Reduced fire risk encourages the adoption of agroforestry practices that boost both carbon storage and agricultural productivity. Lower wildfire risks decrease the financial burden of fire suppression, infrastructure repair, and agricultural losses. Communities reliant on natural resources for farming, forestry, and grazing benefit from reduced disruptions caused by fire events.

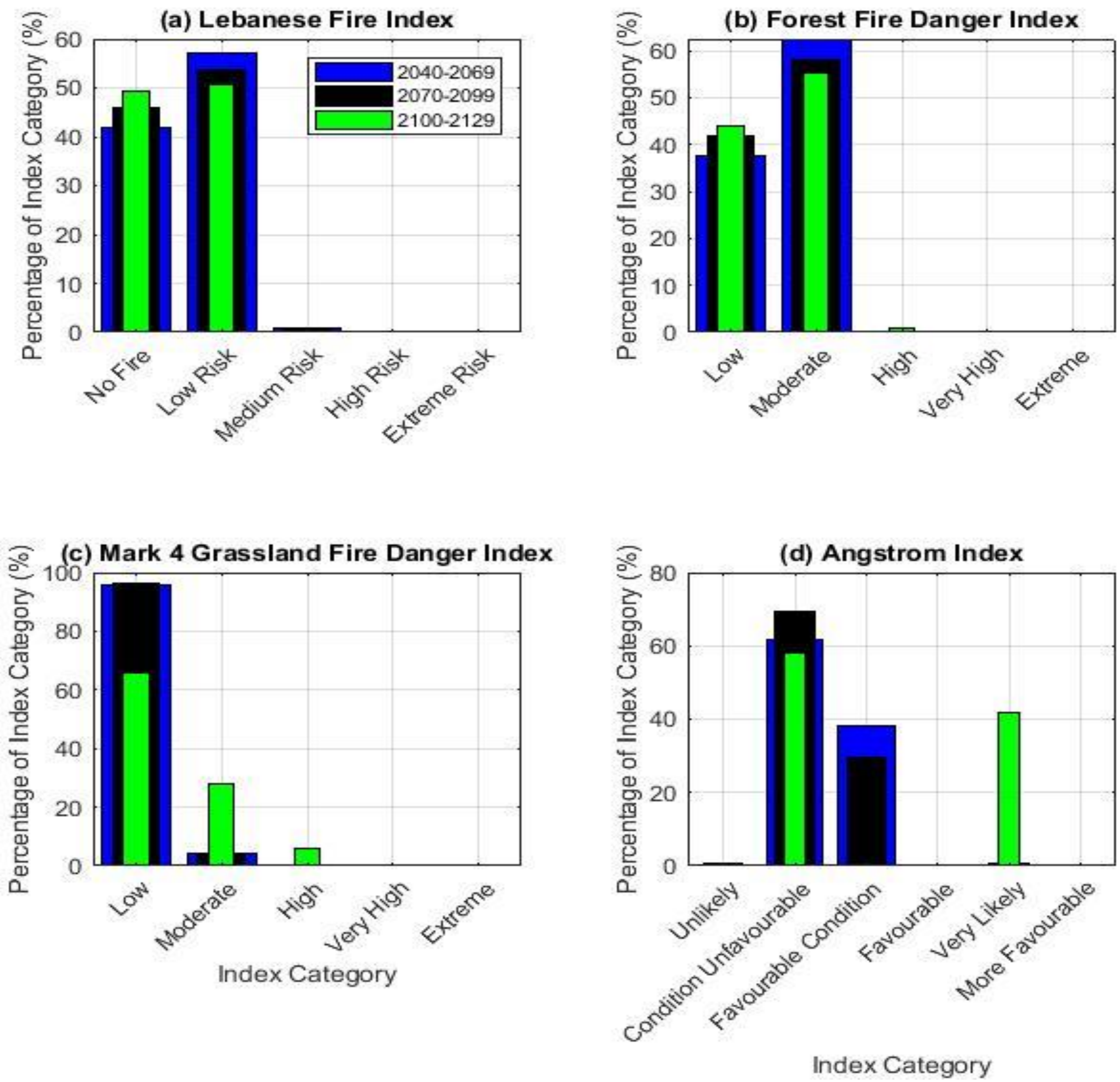

Fig. 2 Histogram showing the percentage of different index categories for each period by (a) Lebanese Index (b) forest fire danger index, (c) Mark 4 grassland fire danger index, and (d) Angstrom index.

Furthermore, each of the index plots (Figs. 3 – 6) for each period shows variations in the fire risk categories within West Africa. The Lebanese index (Fig. 3) shows that there is generally a low risk of fire occurrence (Table 1) in most locations across the Sahel and Guinea Savanna. The Angstrom Index values are usually high at times of low risk or flammability and low at times of high risk or flammability. High values are projected toward the Guinea Savanna (Fig. 4), indicating low risk or flammability is expected at the Guinea Savanna region. Both Forest Fire and Mark 4 Grassland Fire Danger Indices (Figs. 5 and 6) also show that low risk is predominant in Guinea Savanna during all periods, whereas Sahel is moderate. Carbon dioxide removal engenders a decrease in the temperature of Sahel (Uzoma *et al.,* 2023). The decreased temperature coupled with its desert nature will definitely make no provision for any combustibles to be burned; hence the reason for prevalence of low and moderate risk categories of fire occurrence in Sahel. Heat stress also decreased in Sahel under carbon dioxide removal (Uzoma and Adeniyi, 2025). Most of the locations, such as Cote D'Ivoire, Ghana, Burkina Faso, Togo, Benin, and Nigeria, identified as having high potentials for fire occurrences (NASA, 2009), are among the locations within the Guinea Savanna where low risk category is captured by all the indices under carbon dioxide removal scenario. The presence of forest or biomass in Guinea Savannah under carbon dioxide removal serves as a fire extinguisher because the wet season supports vegetation growth. Due to carbon dioxide removal, extreme dry seasons that create favorable conditions for the drying of vegetation and eventually result in fire outbreaks are not projected. In addition, soil moisture due to the existence of forest vegetation discourages the start of fire. The presence of soil moisture contributes to the predominance of the low-risk category of fire conditions in this location because it remains high in the forest region, thus inhibiting and limiting fire propagation (N'Datchoh *et al.*, 2015).

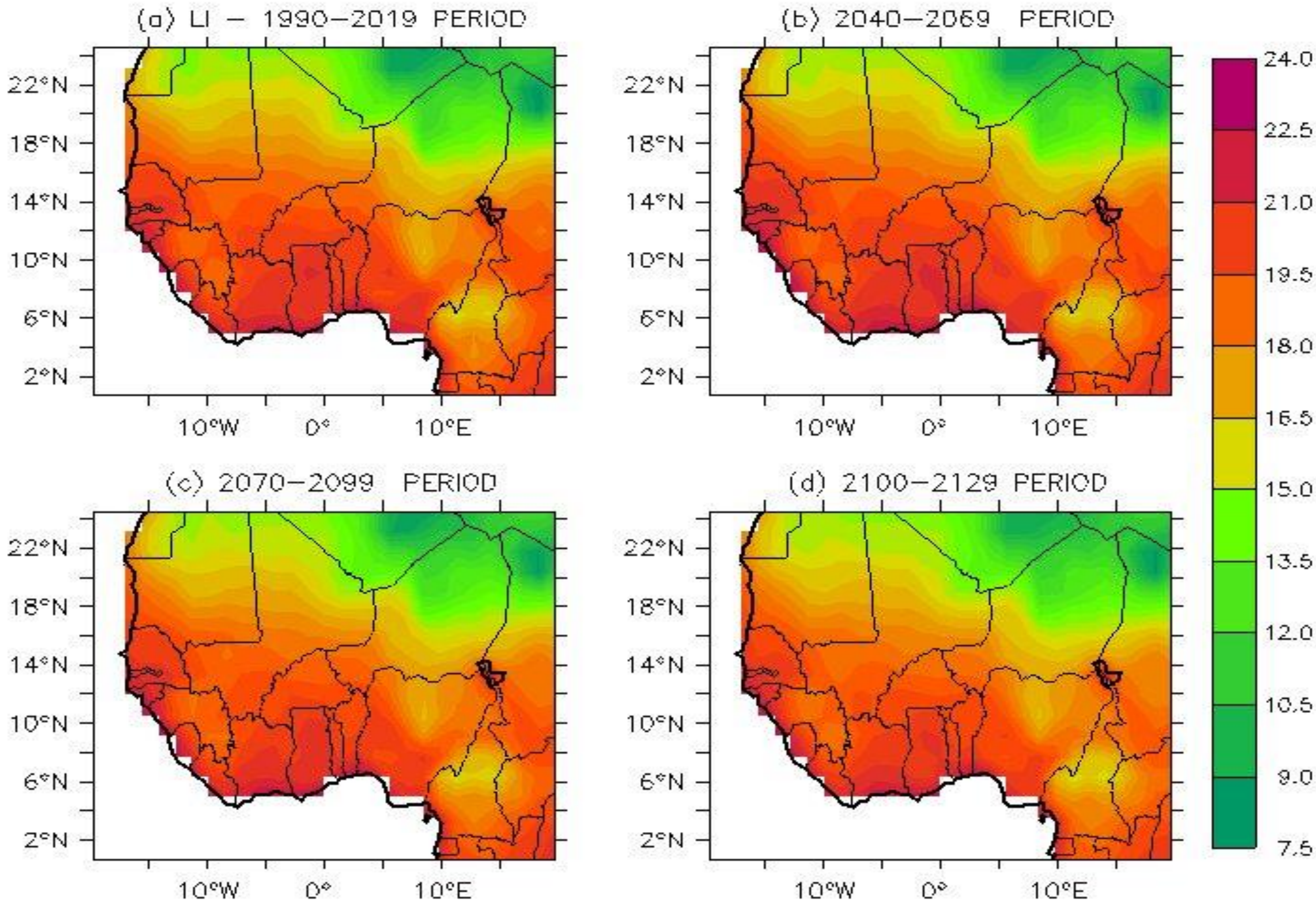

Fig. 3 Lebanese Fire Index values for each of the periods. (a) is the reference period (1990-2019), (b – d) The projected periods 2040–2069, 2070–2099, and 2100–2129

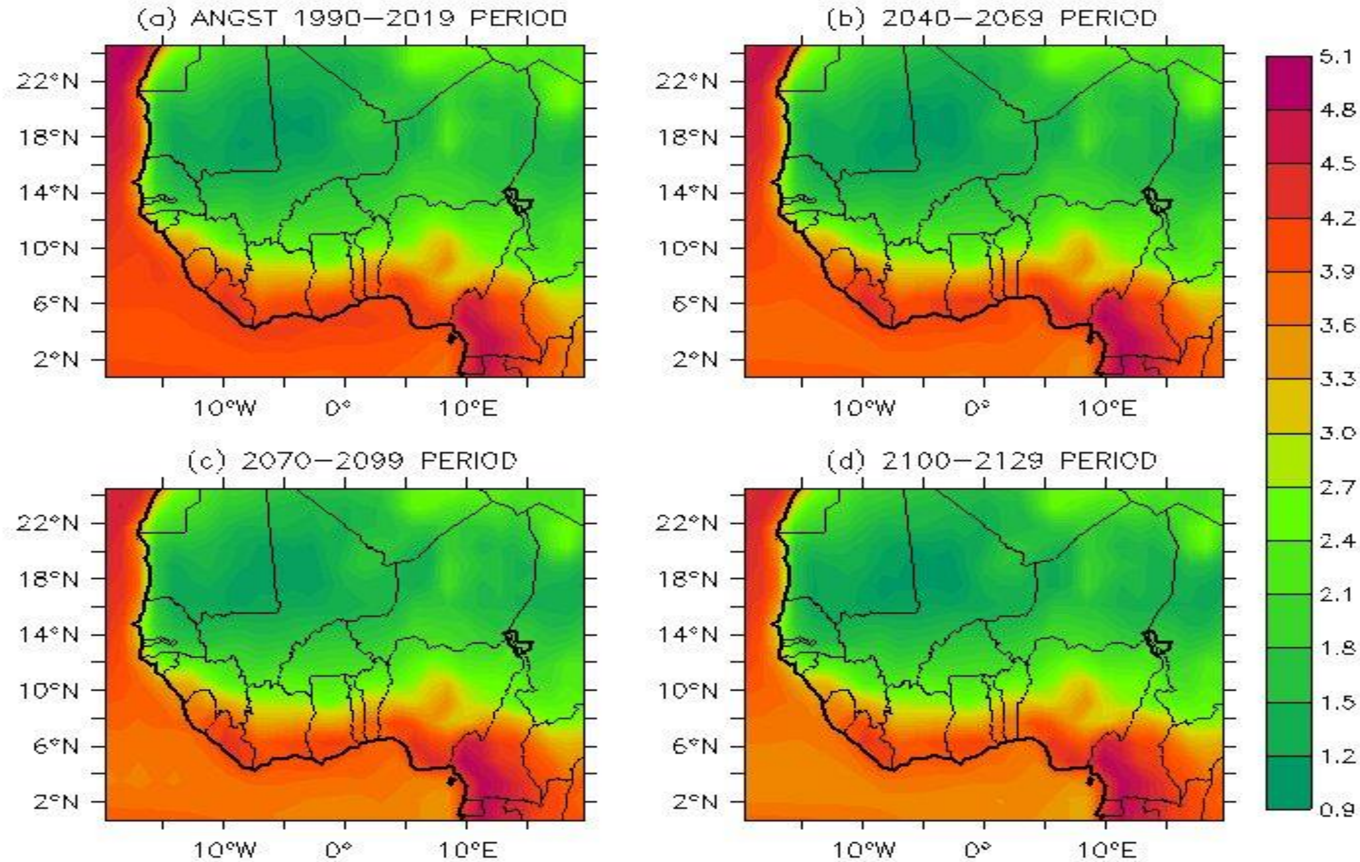

Fig. 4 Angstrom Fire Index values for each period. (a) Reference period (1990-2019), (b – d) projected periods 2040–2069, 2070–2099, and 2100–2129

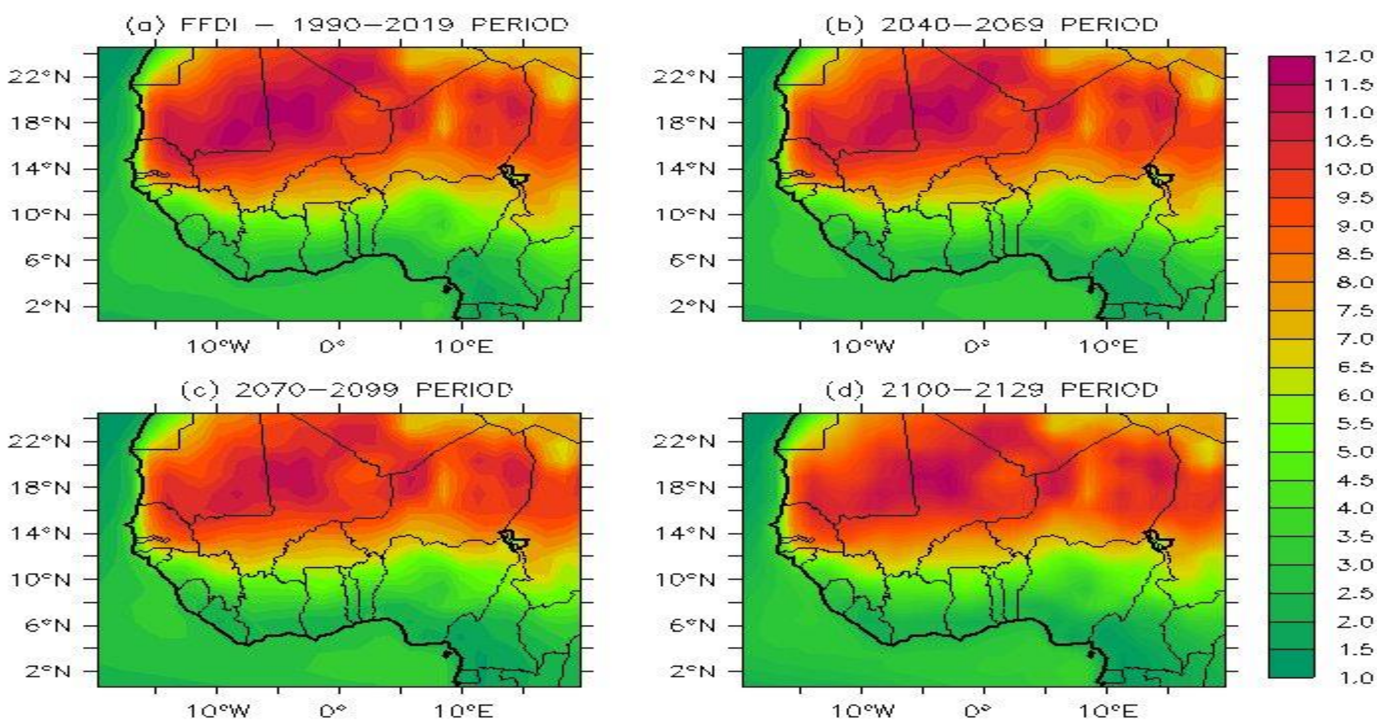

Fig. 5 Forest Fire Danger Index values for each of the periods. (a) The reference period (1990-2019), (b – d) the projected periods 2040–2069, 2070–2099, and 2100–2129

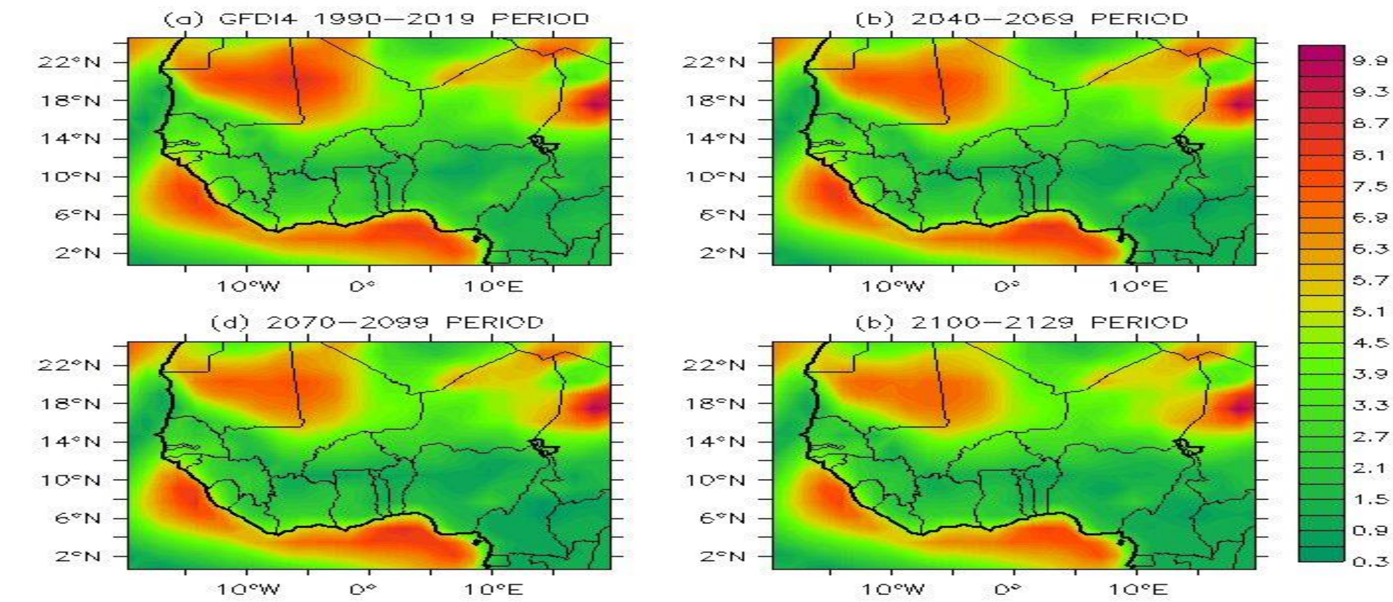

Fig. 6 Mark 4 Grassland Fire Danger Index values for each period. (a) Reference period (1990-2019), (b – d) projected periods 2040–2069, 2070–2099, and 2100–2129

Table 4: Average fire index value and category per period within the locations indicated by the black box in Fig. 7(d).

Indices	2040-2069 Period	2070-2099 Period	2100-2129 Period
FFDI	**7.97** (Moderate Risk)	**7.58** (Moderate Risk)	**7.07** (Moderate Risk)
GFDI4	**1.28** (Low Risk)	**1.17** (Low Risk)	**1.10** (Low Risk)
LEBANESE INDEX (LI)	**12.14** (No Fire Risk)	**11.45** (No Fire Risk)	**10.58** (No Fire Risk)
ANGSTROM INDEX (AI)	**2.34** (Fire Condition Favorable)	**2.5** (Fire Condition Unfavorable)	**2.68** (Fire Condition Unfavorable)

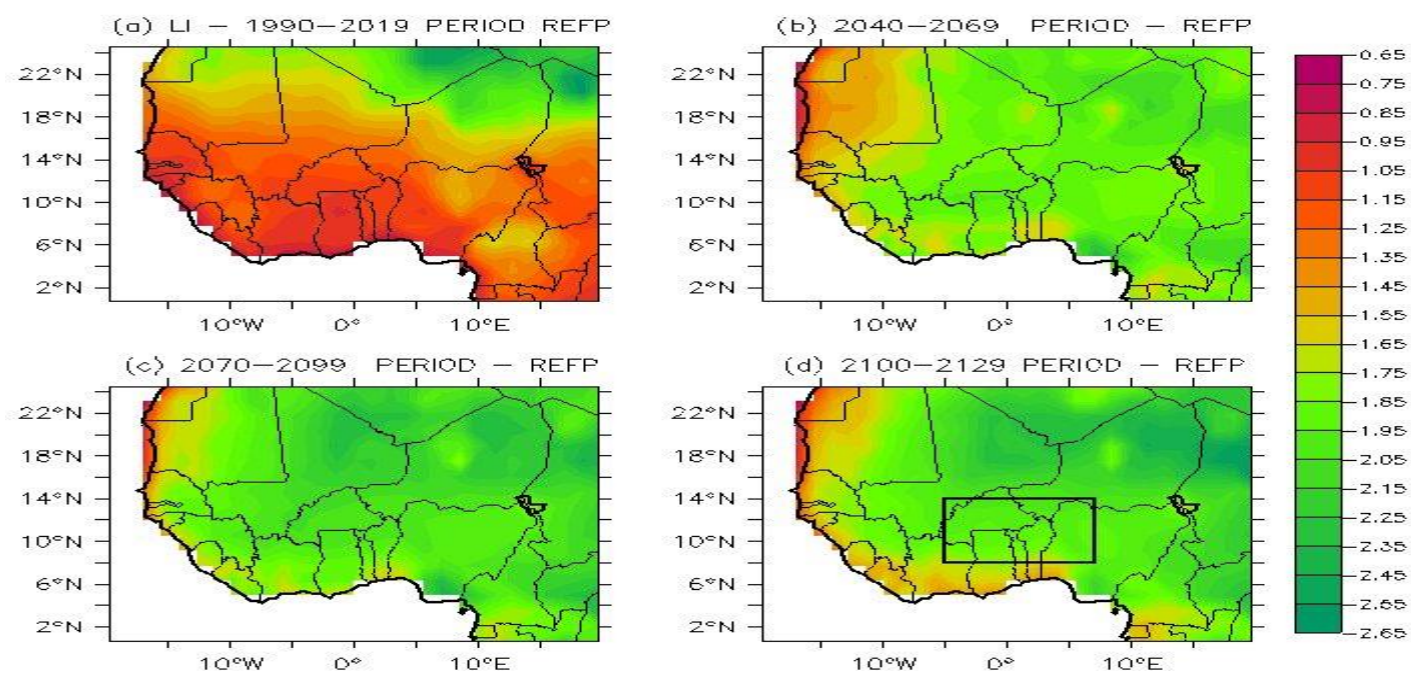

Fig. 7 Lebanese index of differences between each period and the reference period at 5% significant level. The black box shows the locations with higher levels of fire index reduction

From Fig. (7b), the locations identified in the box (Fig. 7(d)), which cut across Cote D'Ivoire, Ghana, Burkina Faso, Togo, Benin, and Nigeria, have lesser impacts in terms of wildfire reduction in period 2040-2069, with respect to the reference period. However, greater impacts are simulated for 2070-2099 and 2100-2129 period within the same locations (Fig. 7 (c and d)). It has been shown from the indices (Table 4) that these locations, being fire destinations in West Africa, will experience no extreme fire conditions but will witness a prevalence of friendly fire risk categories where favorable weather conditions and a high grass moisture content will be dominant. Conditions under which fire catches and spreads will not be sustained in these locations during the phase of atmospheric carbon dioxide removal. An increase in the atmospheric carbon dioxide concentration causes a warming temperature, which makes it possible for severe and adverse fire conditions to thrive. Many environmental impacts associated with climate change can affect the severity and timing of wildfire seasons, including changes in temperature, precipitation, and drought. Short-term weather conditions (dryness, temperature, wind, and lightning) influence the likelihood of ignition, where and how quickly a fire spreads, and how big it gets. Longer-term climate patterns also play a role by creating conditions that may be conducive to wildfires. Human activities and land management practices also affect wildfire activity (US EPA, 2023).

5. Conclusion

Wildfires have a great impact on the environment, not only in the form of air pollution, but by releasing millions of tonnes of CO_2 and other greenhouse gases into the atmosphere, contributing to climate change. Climate change also prepares ground and creates favorable conditions for wildfires to start and spread through increased air and soil temperatures, orchestrated by rise in atmospheric carbon dioxide concentrations. The indices have shown that there will be more of "Low Risk" range of fire index over West Africa in the subsequent or future periods. "Low Risk" of fire means that little or no risk from fire because of climate change should be expected if carbon dioxide removal techniques are implemented. This suggests that West Africa will experience favorable weather and high moisture content of grasses and other dry organic material on the ground during the projected periods with the removal of carbon dioxide from the atmosphere. Locations within the Guinea Savanna will be largely impacted in terms of reduction in fire occurrence. Lower categories of the fire index prevailed in the periods, while no extreme cases of fire occurrence should be expected down the periods. The risk of fire occurrence drastically reduced in those locations identified as fire-prone areas in West Africa.

The stability provided by low fire risk creates a conducive environment for long-term planning and investments in land-use projects. The predominance of low fire risk underlines the potential of CDR to mitigate one of the stressors amplified by climate change, ensuring stability in regions prone to fire-related disasters, such as West Africa. Reduced fire occurrence prevents land degradation and maintains soil moisture, indirectly supporting water balance and reducing aridity. The low-risk category for fire occurrence during CDR studies in West Africa suggests a favorable outcome for the region's ecosystems, agriculture, and communities. The study highlights the potential benefits of CDR beyond carbon removal, such as enhanced resilience, sustained productivity, and reduced vulnerability to climate-induced hazards like wildfires.

Acknowledgment

We acknowledge the Carbon Dioxide Removal Model Intercomparison Project leaders and steering committee who are responsible for CDRMIP, and we thank the climate modeling groups for producing and making their model output available for use in this research.

References

Abatzoglou, J. T., and Kolden, C. A. (2013). Relationships between climate and macroscale area burned in the western United States. International Journal of Wildland Fire 22 **(7),** 1003–1020. Doi:10.1071/WF13019.

Andreae, M. O., and Merlet, P. (2001). The emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15:955

Balch, J. K., Bradley, B. A, Abatzoglou J. T and Mahood, A. L. (2017). Human-started wildfires expand the fire niche across the United States. Proceedings of National Academy of Science U. S. A. https://doi.org/10.1073/pnas.1617394114

Balmes, J. R. (2020). Where there's smoke, kids will cough and wheeze. Annals of the American Thoracic Society, **17**(3), 276–277. https://doi.org/10.1513/AnnalsATS.201910-728ED

Bond, W. J. (2008. What limits the use of trees in C4 grasslands and savannas? *Annual Review* of *Ecology*, *Evolution*, and Systematics, 39, 641–59.

Burrell, A., Kukavskaya, E., Baxter, R., Sun, Q., and Barrett, K. (2021). Post-fire recruitment failure as a driver of forest to non-forest ecosystem shifts in boreal regions. In J. G. Canadell & R. B. Jackson (Eds.), Ecosystem Collapse and Climate Change (pp. 69–100). Springer International Publishing. https://doi.org/10.1007/978-3-030-71330-0_4

Burrell, A. L., Evans, J. P., and De Kauwe, M. G. (2020). Anthropogenic climate change has driven over 5 million km^2 of drylands toward desertification. Nature Communications, **11**(1), 3853. https://doi.org/10.1038/s41467-020-17710-7

Caillault, S. Le feu, la brousse and la savane (2011). Modelisation spatiale de la dynamique des paysages soudaniens (Burkina Faso). Ph. D. Thesis, University de Caen Basse, Normandie, France.

Center for Climate and Energy Solutions, (2023). Wildfires and Climate Change. https://www.c2es.org/content/wildfires-and-climate-change/

Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R .D., Coakley, J. A., Hansen, J. E., and Hofmann, D. J. (1992). Climate Forcing by Anthropogenic Aerosols. Science, 255, 423–430.

Climate Reality Project (2023). Wildfires and the climate crisis. https://www.climaterealityproject.org/blog/wildfires-and-climate-crisis

Danthu, P., M. Ndongo, M. Diaou, O. Thiam, A. Sarr, B. Dedhiou, and A. Ould Mohamed Vall, A. (2003). Impact of bush fire on germination of some West African acacias. Forest Ecology and Management, 173(1), 1–10.

Devineau, J. L., Fournier, A. and Nignan, S. (2010). Assessing Savanna fire regimes assessment with MODIS fire data: Their relationship to land cover and plant species distribution in western Burkina Faso (West Africa). Journal of Arid Environment, 74, 1092–101.

Environmental Defense Fund 2023. Climate Change and Wildfires. Retrieved from https://www.edf.org/climate/heres-how-climate-change-affects-wildfires

Eyring, V., Bony, S., Meehl, G .A., Senior, C .A., Stevens, B., Stouffer, R.J. and Taylor, K.E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization; Geoscience Model Development, **9** 1937–1958 https://doi.org/10.5194/gmd-9-1937-2016.

FAO. (2007). Fire Management and Global Assessment.

Giglio, L., Randerson, J.T., van der Werf, G.R., Kasibhada, P.S., Collatz, G.J., Morton, D.C. and de Fries, R.S. (2010). Assessing variability and long-term trends in burned areas by merging multiple satellite fire products. Biogeosciences, 7, 1171–1186.

Global Forest Resources Assessment (2000). Global issues. Chapter 8. Fire https://www.fao.org/3/Y1997E/y1997e0d.htm#bm13.

Gomes, J.F.P. (2006). Forest fires in Portugal: How do they happen and why they happen. International Journal of Environmental Studies, 63(2), 109–119. DOI: 10.1080/00207230500435304.

Grégoire, J. M., Eva, H.D., Belward, A.S., Palumbo, I., Simonetti, D., and Brink, A. (2013). Effect of land-cover change on Africa’s burnt area. International Journal of Wildland Fire, 22, 107–120.

Hamadeh, N., Karouni, A., Daya, B., and Chauvet, P. (2017). Using correlative data analysis to develop weather index that estimates the risk of forest fires in Lebanon: Assessment versus prevalent meteorological indices, European Journal of Agriculture and Forestry Research 5(1), Pp.9-34.

Hansen, J., Sato, M., and Ruedy, R. (1997). Radiative forcing and climate response. Journal of Geophysical Research, 102, 6831–6864.

He, T., Lamont, B. B., and Pausas, J. G. (2019). Fire as a key driver of Earth’s biodiversity. Biological Reviews, **94**(6), 1983–2010. https://doi.org/10.1111/brv.12544

Hirota, M., Holmgren, M., Van Nes, E. H., and Scheffer, M. (2011). Global resilience of tropical forest and savanna to critical transitions. Science, **334**(6053), 232–235. https://doi.org/10.1126/science.1210657

Hope, E. S., McKenney, D. W., Pedlar, J. H., Stocks, B. J., and Gauthier, S. (2016). Wildfire suppression costs for Canada under a changing climate. PLOS One, **11**(8), e0157425. https://doi.org/10.1371/journal.pone.0157425

Johnston, F. H., Borchers-Arriagada, N., Morgan, G. G., Jalaludin, B., Palmer, A. J., Williamson, G. J., and Bowman, D. M. J. S. (2021). Unprecedented health costs of smoke-related PM2.5 from the 2019–20 Australian megafires. Nature Sustainability, **4** (1), 42–47. https://doi.org/10.1038/s41893-020-00610-5

Johnston, F. H., Henderson, S. B., Chen, Y., Randerson, J. T., Marlier, M., DeFries, R. S., et al. (2012). Estimated global mortality attributable to smoke from landscape fires. Environmental Health Perspectives, **120**(5), 695–701. https://doi.org/10.1289/ehp.1104422

Jolly, W. M., Cochrane, M. A., Freeborn, P. H., Holden, Z. A., Brown, T. J., Williamson, G. J., and Bowman, D. M. J. S. (2015). Climate-induced variations in global wildfire danger from 1979 to 2013. Nature Communications, **6**(1), 7537. https://doi.org/10.1038/ncomms8537

Jones, M. W., Abatzoglou, J. T.,Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., Smith, A.J.P., Burton, C., Betts, R.A., vander Werf, R.A., Sitch, S., Canaell, J.G., Santin, C., Kolden, C., Doerr, S.H., and Quere , C.L. (2022). Global and regional trends and fire drivers under climate change. Reviews of Geophysics *60*, e2020RG000726. **https://doi.org/10.1029/2020RG000726**

Joubert, D. F., Smit, G. N., and Hoffman, M. T. (2012). The role of fire in preventing transitions from a grass-dominated state to a bush-thickened state in arid savannas. Journal of Arid Environments, 87, 1–7.

Kabo-Bah, A.T., Amo-Boateng, M., Kabo-Bah, K., Sey, N.E.N., Siabi, E., Okyereh, S., Sarquah, K. (2016b). A Regional Assessment of Wildfires in West Africa. Sendai Framework Implementation. Available at: 65783_f204amoskabobahsendaiframeworkimple.pdf

Kabo-Bah, A. T., Diji, C. J., Nokoe, K., Mulugetta, Y., Obeng-Ofori, D., and Akpoti, K. (2016a). Multiyear rainfall and temperature trends in the Volta river basin and their potential impact on hydropower generation in Ghana. Climate, 4(4), 49.

Kauffman, J.B., Arifanti, V.B., Basuki, I., Kurnianto, S., Novita, N., Murdiyarso, D., Donato, D.C., Warren, M.W. (2016). Protocols for the Measurement, Monitoring, and Reporting of Structure, Biomass, Carbon Stocks, and Greenhouse Gas Emissions in Tropical Peat Swamp Forests. Protocols for the measurement, monitoring, and reporting of structure, biomass, carbon stocks, and greenhouse gas emissions in tropical peat swamp forests (Center for International Forestry Research (CIFOR). https://doi.org/10.17528/cifor/006429.Return to ref 22 in article

Kaufman Y.J. and Tanré, D. (1994). Effect of variations in super-saturation on the formation of cloud condensation nuclei. Nature 369, 45–48.

Keller, D. P., Lenton, A., Littleton, E .W., Oschlies, A., Scott, V., Vaughan, N .E. (2018). The Effects of Carbon Dioxide Removal on the Carbon Cycle. Springer, Current Climate Change Reports 4, *250–265. https://doi.org/10.1007/s40641-018-0104-3.*

Kennedy, P. J., Belward, A. S., and Gregoire, J. M. (1994). An improved approach to fire monitoring in West Africa using AVHRR data. International Journal of Remote Sensing, 15(11), 2235–2255.

Koppmann, R., Von Czapiewski, K., and Reid, J.S. (2005). A review of biomass burning emissions, part I: Gaseous emissions of carbon monoxide, methane, volatile organic compounds, and nitrogen containing compounds. Atmospheric Chemistry and Physics, 5, 10455–10516.

Kraaij, T., and Ward, D. (2006). Effects of rainfall, nitrogen, fire, and grazing on tree recruitment and early survival in bush-encroached savanna, South Africa. Plant Ecology. 186(2), 235–246.

Kull, C.A., and Laris, P. (2009). Fire ecology and fire politics in Mali and Madagascar. In Tropical Fire Ecology: Climate Change, Land Use and Ecosystem Dynamics. Springer: Berlin/Heidelberg, Germany, 2009; pp. 171–226. [**Google Scholar**] [**CrossRef**].

Laris, P. (2013). Integrating Land Change Science and Savanna Fire Models in West Africa. Land**, 2013**, *2*, 609-636. https://doi.org/10.3390/land2040609.

Levine, J.S. (1994). Biomass Burning and the Production of Greenhouse Gases. In Climate Biosphere Interaction: Biogenic Emissions and Environmental Effects of Climate Change; Zepp, R.G., Ed.; John Wiley and Sons: New York, NY, USA, pp. 139–160. [**Google Scholar**].

Loehman, R.A., Reinhardt, E., Riley, K.L. (2014). Wildland fire emissions, carbon, and climate: Seeing the forest and the trees — A cross-scale assessment of wildfire and carbon dynamics in fire-prone, forested ecosystems. Forest Ecology and Management, *317,* 9–19. [**Google Scholar**] [**CrossRef**])

Maslin, M. (2008). Global Warming. A Very Short Introduction. Oxford University Press Inc.

McArthur, A.G. (1966). Weather and grassland fire behavior. Department of National Development, Forestry, and Timber Bureau Leaflet No. 100. Canberra, Australia.

Moris, J. V., Conedera, M., Nisi, L., Bernardi, M., Cesti, G., and Pezzatti, G. B. (2020). Lightning-caused fires in the Alps: identifying the igniting strokes. Agricultural and Forest Meteorology, 290, 107990, https://doi.org/10.1016/j.agrformet.2020.107990.

National Interagency Fire Center (2020). Federal firefighting costs (suppression only). Retrieved from https://www.nifc.gov/fire-information/statistics/suppression-costs.

Rao, K., Williams, A. P., Diffenbaugh, N. S., Yebra, M., Bryant, C. and Konings, A. G. (2023). Dry live fuels increase the likelihood of lightning-caused fires. Geophysical Research Letters, 50, e2022GL100975. https://doi. org/10.1029/2022GL100975

Reddad, H., Etabaai, I., Rhoujjati, A., Taieb, M., Thevenon, F., and Damnati, B. (2013). Fire activity in North West Africa during the last 30,000 cal years BP inferred from a charcoal record from Lake Ifrah (Middle atlas-- Morocco): climatic implications. Journal of African Earth Sciences.

Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R., and Elliott, C. T. (2016). Critical review of health impacts of wildfire smoke exposure. Environmental Health Perspectives, **124** (9), 1334–1343. https://doi.org/10.1289/ehp.1409277

Roberts, G., Wooster, M.J. and Lagoudakis, E. (2009). Annual and diurnal African biomass-burning temporal dynamics. Biogeosciences 6, 849–866. doi:10.5194/BG-6-849-2009

Roudier, P., Sultan, B., Quirion, P., and Berg, A. (2011). Impact of future climate change on West African crop yields: What is the recent literature? Global Environmental Change, 21(3), 1073–1083.

Scholes, R. J., and Archer, S. R. (1997). Tree-grass interactions in Savannas. Annual Review, 28: 517-544. https://doi.org/10.1146/annurev.ecolsys.28.1.517

Schunk, C., Leutner, C., Leuchner, M., Wastl, C., Menzel, A. (2013). Equilibrium moisture content of dead fine fuels of selected central European tree species. International Journal of Wildland Fire 22(6):797-809.

Shlisky, A., Alencar, A., Nolasco, M.M. and Curran, L. (2009). Overview: Global fire regime conditions, threats, and opportunities for fire management in the tropics In Tropical Fire Ecology (pp. 65–83). Berlin/Heidelberg, Germany: Springer; 2015.

Staver, A. C., Archibald, S., Levin, S. A. (2011). The global extent and determinants of savanna and forest as alternative biome states. Science, **334**(6053), 230–232. https://doi.org/10.1126/science.1210465

Stocks, B. J., and Martell, D. L. (2016). Forest fire management expenditures in Canada: 1970–2013. The Forestry Chronicle, **92** (03), 298–306. https://doi.org/10.5558/tfc2016-056

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M. and Baron, C. (2013). Assessing the impacts of climate change on sorghum and millet yields in the Sudanian and Sahelian Savanna of West Africa. Environmental Research Letters, 8(1), 14040.

Tymstra, C., Bryce, R., Wotton, B., Taylor, S., and Armitage, O. (2010). Northern Forestry Center (Canada): Development and structure of Prometheus: The Canadian wildland fire growth simulation model. Northern Forestry Center. Retrieved from https://central.bac-lac.gc.ca/.item?id=31775&op=pdf&app=Library.

Uzoma, E.K. and Adeniyi, M.O. (2025). Projected heat/cold waves and heat stress conditions in West Africa under carbon dioxide removal scenarios. Modelling Earth System and Environment, 11(112). https://doi.org/10.1007/s40808-025-02297-z

Uzoma, E. K., Adeniyi, M. O., Keller, D. P., Seferian, R., and Oladiran, E. O. (2023). The impact of carbon dioxide removal on temperature parameters over West Africa; Meteorology and Atmospheric Physics, 135(55). https://doi.org/10.1007/s00703-023-00992-z.

Van Lierop, P., Lindquist, E., Sathyapala, S., and Franceschini, G. (2015). Global forest area disturbance due to fire, insect pests, diseases, and severe weather events. Forest Ecology and Management, 352, 78-88.

Vernooij, R., Giongo, M., Borges, M. A., Costa, M. M., Barradas, A. C. S., and van der Werf, G. R (2021). Intraseasonal variability of greenhouse gas emission factors from biomass burning in the Brazilian Cerrado. Biogeosciences, 18, 1375–1393, https://doi.org/10.5194/bg-18-1375-2021, 2021.

Ward, M., Tulloch, A. I. T., Radford, J. Q., Williams, B. A., Reside, A. E., Macdonald, S. L., et al. (2020). Impact of 2019–2020 mega-fires on Australian fauna habitat. Nature Ecology & Evolution, **4**(10), 1321–1326. https://doi.org/10.1038/s41559-020-1251-1

Wimberly, M.C., Wanyama, D., Doughty, R., Peiro, H., and Crowell, S. (2024). Increasing Fire Activity in African Tropical Forests Is Associated With Deforestation and Climate Change. Geophysical Research Letters, 51(9). https://doi.org/10.1029/2023GL106240

Yaro, V.S.O., Bondé, L., Bougma, Pt.C, Sedgo I, Guuroh, R.T, Gebremichael A.W., Neva, T., Linstadter, A., and Ouedraogo, O. (2024). Greenhouse gas emission from prescribed fires is influenced by vegetation types in West African Savannas. Scientific Report, **14**, 23754. https://doi.org/10.1038/s41598-024-73753-6

Yongkang, X., Aaron, B., Christopher, M.T. (2012). Review of Recent Developments and the Future Prospective in West African Atmosphere/Land Interaction Studies. International Journal of Geophysics, ID 748921, 12 pages, https://doi.org/10.1155/2012/748921.

Zafar, S .A., Hameed, A., Nawaz, M .A., Wei, M .A., Noor, M .A., Hussain, M., and Rahman, M. (2018). Mechanisms and molecular approaches for heat tolerance in rice (*Oryza sativa* L.) under climate change scenario. Journal of Integrative Agriculture, **17** (**4**) 726-738.