Université de Lomé **ED730-LH** WASCAL

SPONSORED BY THE Federal Ministry of Education and Research

N° d'Ordre : 026

THÈSE DE DOCTORAT

Présentée pour l'obtention du grade de

DOCTEUR DE L'UNIVERSITÉ DE LOMÉ

Ecole Doctorale Lettres et Humanités ED730-LH

West African Science Service Centre on Climate Change and Adapted Land Use

Domaine : Sciences de l'Homme et de la Société

Mention : Changement Climatique et Sécurité Humaine

Spécialité : Changement Climatique et Gestion des Risques de Catastrophes

Par

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WILDFIRE EFFECTS ON SAVANNAH ECOSYSTEM IN THE NORTHERN PART OF GHANA AMIDST A CHANGING CLIMATE

Soutenue publiquement le **27 Fevrier 2025** devant le jury composé de :

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ED730-LH

SPONSORED BY THE Federal Ministry of Education and Research

Order No.: 026

DOCTORAL THESIS

Presented for the award of the grade of

DOCTOR OF THE UNIVERSITY OF LOMÉ

School of Letters and Humanities ED730-LH

West African Science Service Center on Climate Change and Adapted Land Use

Field: Human and Social Sciences

Specialization : Climate Change and Human Security..........

Specialty: Climate change and disaster risk management

By

Aline Mwintome NAAWA

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Publicly defended on 27th February 2025 before the jury composed of:

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WILDFIRE EFFECTS ON SAVANNAH ECOSYSTEMS IN THE NORTHERN PART OF GHANA AMIDST A CHANGING CLIMATE

DOCTORAL DISSERTATION

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WASCAL

February, 2025

TABLE OF CONTENT

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

DEDICATION

To God Almighty, who is, who was and who is to come!

To my big sister **Esthere Synthia Some**, thank you for playing the role of a mother and a sister.

To the eternal memory of my auntie (**Mrs. Prudence N. Gyader**). Her unwavering belief in my abilities, her sacrifices to support my education, and the values she instilled in me have been the cornerstone of my academic journey. This work is a testament to her enduring influence on my life.

To my husband and children (**Daniel, Daisy, Delvon and Daryl**), for the encouragement when the going became tough

ACKNOWLEDGEMENTS

My help comes from the Lord, the Maker of heaven and earth. I give him all the praise and adoration for a successful PhD Journey. As I geared up for this journey, I had no idea what roadblocks awaited me, but I promised to keep myself going, and here I am, at the finish line! Of course, no journey comes without a few bumps and roadblocks; I felt disappointment, some of which felt like a bee stung, but these were just redirections (I sure did not love hearing that then).

First and foremost, I am forever indebted to the West African Climate Change and Adapted Land Use (WASCAL) program with funding from the German Federal Ministry for Education and Research, which provided financial support for my research project, without which I would not have been able to undertake this journey.

I am also extremely grateful to my main supervisor **Dr. Fousséni Folega**, for his unwavering guidance, patience, and encouragement throughout this journey. His profound knowledge and critical insights have shaped the direction of this work and contributed immensely to its completion.

Additionally, I am deeply grateful to my co-supervisors, Prof. Amos Kabo-bah and Dr. Yvonne Walz, for their continuous support, technical expertise, and invaluable contributions. Their mentorship and willingness to guide at every research stage have been invaluable and instrumental in shaping this work. Their constant support and encouragement motivated me throughout the journey and gave me a reason not to quit.

My appreciation also goes to the external examiners, **Prof Tchaa Boukpessi** and **Prof. Raymond Aabeyir**, for their insightful feedback and valuable recommendations, which have significantly enriched this research. Their expertise and constructive criticism have been instrumental in refining the study's focus and ensuring its academic rigor.

I particularly appreciate the support from WASCAL Lome, the Director **Prof Komi Agboka**, and Deputy Director **Prof Begedou Komi**, who acted as not only directors but also our fathers away from home. I appreciate their ever-ready presence to solve any challenge I bring along your way. I would also like to thank the scientific coordinator, **Dr Mouhammed Iddrissou**, for constantly sharing opportunities and being ready to offer any form of assistance, **Madam Sefakor**, **Mr Folly Kuevi**, and all the other staff of WASCAL who made sure my stay in Lome was memorable and devoid of any challenges. I also extend my profound gratitude to the EVES team, EHS Department of the United Nations University Bonn, for making me feel at home and contributing meaningfully to my work in any possible way.

This research also made me work with people who will forever be embedded in my life history: **Mr. Bilouktime Badjaré, Mr. Satigou Wonepo, Mr. Labdiedo Pakidam, Mr. Loabi Arzouma, Mr. Amos**

Amponsah, Mr. Elvis Brenya Appiah-Kusi, Dr. Mike Amatus, and **Dr. Reginald Gurroh** (CRIG) for assisting in various aspects of the work.

I want to thank the various individuals, including **Dr. Polycarp Mabier** of the Ghana Forestry Department and his Staff, who participated in the fieldwork and provided critical data on wildfire dynamics and ecosystems. I also want to thank **Dr. Adriana Ford** of the Leverhulme Center for Wildfires, Kings College, London, for constantly checking up on me and showing genuine interest in my work. Their cooperation and support were vital to the success of this project.

To my colleagues with whom I have developed camaraderie and a lifelong bond and with whom I will have the opportunity to visit seven countries in West Africa without being stranded, thank you for your encouragement and the many constructive discussions that helped me refine my ideas and approach.

Lastly, I want to thank my family (**Esthere, Jean Bosco, and Thomas D'aquin**) for their love, patience, and unwavering belief in me throughout this journey. Their support has been my constant source of motivation.

To all who contributed to this thesis in one way or another, I offer my sincere appreciation.

ABSTRACT

Wildfires in Ghana's part of the Northern Savannah zone have recently become a primary environmental and socio-economic concern due to climate change and human activities. The aftermath of such a fire can be stretched toward species composition, vegetation structure, and resilience in ecosystem services. For that reason, a careful consideration of its impact and management strategies is imperative. This work systematically evaluated wildfire management strategies at national and local scales, wildfire drivers and impacts were examined, and the effects of wildfires on Northern Ghana's ecosystem structural diversity and vegetation dynamics were assessed. Using a mixed-method approach combining remote sensing data from MODIS-NDVI ground truthing to understand the status of area wildfires from 2000 to 2021, this research analysed climatic variables from 1992 to 2022 relevant to temperature, humidity, and wind speed with fire patterns. Additionally, species composition was studied across frequently burned and non-burned plots, considering fire-tolerant and fire-sensitive species. The analysis used OLS and GWR models to anchor our understanding of the spatial pattern of the wildfires and their driving factors, such as land use and proximity to settlements. The findings reveal that within the study area, active fires number 432,153, with the highest in West Gonja and Mamprugu Moagduri. At the same time, the most significant wildland fire occurrence predictors were proximity to the settlements, slope gradient and temperature, and the most influential was maximum temperature at $p < 0.01$. Fire-resistant species, such as *Vitellaria paradoxa* and *Parkia biglobosa*, were abundant in most areas affected by the fire. The populations of fire-intolerant species, such as *Khaya senegalensis*, declined considerably. Species richness was 15% lower in the frequently burned areas, and there was a significant shift towards shrubland expansion at the expense of forest cover. The study also identified a decreased burned area over time, $p = 0.015$, although no significant trend in fire frequency, $p = 0.499$, was detected. Wildfires threaten savannah ecosystems by reducing biodiversity, altering vegetation, and degrading ecosystem services, with human activities and climate change intensifying their impact. However, integrating wildfire prevention into climate policies, afforestation, controlled burning, and early warning systems can enhance ecosystem resilience in Ghana’s savannah zone.

Keywords: Wildfires, Savanna ecosystems, Species composition, Climate adaptation, Remote Sensing, Biodiversity Loss

RÉSUMÉ

Les incendies de forêt dans la zone septentrionale de la savane au Ghana sont récemment devenus une préoccupation environnementale et socio-économique majeure en raison du changement climatique et des activités humaines. Les conséquences de tels incendie peuvent avoir des répercussions sur la composition des espèces, la structure de la végétation et la résilience des services écosystémiques. C'est pourquoi il est impératif d'examiner attentivement leur impact et les stratégies de gestion. Ce travail a systématiquement évalué les stratégies de gestion des incendies de forêt à l'échelle nationale et locale ; après avoir examiné les causes et les impacts des incendies de forêt en général, l'étude a évalué les effets des incendies de forêt sur la diversité structurelle de l'écosystème du nord du Ghana et sur la dynamique de la végétation. À l'aide d'une méthode mixte combinant des données de télédétection provenant de la vérification au sol MODIS-NDVI pour comprendre l'état des feux de forêt dans la région entre 2000 et 2021, cette recherche a analysé les variables climatiques entre 1992 et 2022 concernant la température, l'humidité et la vitesse du vent avec les schémas d'incendie. En outre, la composition des espèces a été étudiée dans les parcelles fréquemment brûlées et non brûlées, en tenant compte des espèces tolérantes et sensibles au feu. L'analyse a utilisé des modèles OLS et GWR pour ancrer notre compréhension de la configuration spatiale des incendies de forêt et de leurs facteurs déterminants, tels que l'utilisation des terres et la proximité des zones habitées. Les résultats révèlent que dans la zone d'étude, les feux actifs sont au nombre de 432 153, les plus importants se trouvant à Gonja Ouest et Mamprugu Moagduri. Dans le même temps, les prédicteurs les plus significatifs de l'occurrence des incendies de forêt sont la proximité des établissements, le gradient de pente et la température ; la température maximale étant la plus influente avec un $p < 0{,}01$. Les espèces résistantes au feu, telles que *Vitellaria paradoxa* et *Parkia biglobosa*, étaient abondantes dans la plupart des zones touchées par l'incendie. Les populations d'espèces intolérantes au feu, telles que *Khaya senegalensis*, ont considérablement diminué. La richesse en espèces était inférieure de 15 % dans les zones fréquemment brûlées, et l'on a observé une évolution significative vers l'expansion des arbustes au détriment de la couverture forestière. L'étude a également mis en évidence une diminution de la superficie brûlée au fil du temps ($p = 0{,}015$), bien qu'aucune tendance significative n'ait été détectée en ce qui concerne la fréquence des incendies ($p = 0{,}499$). Les incendies de forêt menacent les écosystèmes de savane en réduisant la biodiversité, en altérant la végétation et en dégradant les services écosystémiques, les activités humaines et le changement climatique intensifiant leur impact. Cependant, l'intégration de la prévention des incendies dans les politiques climatiques, le boisement, le brûlage contrôlé et les systèmes d'alerte précoce peuvent améliorer la résilience des écosystèmes dans la zone de savane du Ghana.

Mots-clés : Incendies de forêt, écosystèmes de savane, composition des espèces, adaptation au climat, télédétection, perte de biodiversité.

LIST OF ACRONYMS AND ABBREVIATIONS

AJOL	African Journals Online
AICc	Akaike Information Criterion
ANN	Annual Average Temperature
ANOVA	Analysis of Variance
BA	Basal Area
CCA	Canonical Correlation Analysis
DBH	Diameter at Breast Height
DCA	Detrended Correspondence Analysis
DEM	Digital Elevation Model
FRP	Fire Radiative Power
GC	Guineo-Congolese
GC-SZ	Guineo-Congolese and Sudano-Zambezi
GIS	Geographic Information System
GLMM	Generalised Linear Mixed Model
GWR	Geographically Weighted Regression
GPS	Global Positioning System
FAO	Food and Agriculture Organization
GSS	Ghana Statistical Service
IDW	Inverse Distance Weighted
IVI	Importance Value Index
JB	Jarque-Bera
LULC	Land Use Land Cover
MEA	Millennium Ecosystem Assessment
MODIS	Moderate Resolution Imaging Spectroradiometer
MP	Megaphanerophytes
NASA	National Aeronautics and Space Administration
NDVI	Normalised Difference Vegetation Index
NIR	Near-Infrared
NOAA	National Oceanic and Atmospheric Administration
OLS	Ordinary Least Squares
Pal	Paleotropical
Pan	Pantropical
SCOPUS	Elsevier's Abstract and Citation Database
SCP	Semi-Automatic Classification Plugin
SZ	Sudano-Zambezi
VIF	Variance Inflation Factor

GENERAL INTRODUCTION

Wildfires are a key perturbative force in environments worldwide, including forests, savannahs, and grassland environments. Fire can naturally occur, with a high probability of being started through lightning during droughts. However, it can also be started through such actions as agricultural expansion, land use, and accidental fires (Andela et al., 2017). Fire is a key mechanism for regeneration and conservation in specific ecosystems. For instance, North America's prairies, Mediterranean woodlands, and Australian bushland depend on periodic fires for regeneration and diversity conservation (Bowman et al., 2009). However, in non-fire-adapted ecosystems, frequent and intense fires can result in loss of biodiversity, degradation of the soil, and a disruption in the hydrological cycle (Flannigan et al., 2009).

Climate change heightened wildfire risk globally by warming temperatures, altering precipitation patterns, and prolonged droughts. All these have aided in developing a heightened and intenser wildfire, for instance, in regions such as Australia, Amazon, and the western United States of America. Wildfires impact Ecosystem services greatly, with a lot of carbon released into the atmosphere, amplifying climate change (Archibald et al., 2017).

The African savannahs are one of the most combustible landscapes globally, covering vast areas across sub-Saharan Africa. These ecosystems are generally characterised by a mixture of grasses and scattered trees with a distinct wet and dry season. Fire has been a natural part of African savannahs for millennia, playing a crucial role in maintaining the balance between grasses and woody plants (Sankaran et al., 2005). Fires caused by lightning naturally occur at the end of the dry season, regulating tree density, cycling nutrients, and preventing the encroachment of woody vegetation, which otherwise would disturb the ecological balance (Archibald et al., 2009). Most traditional communities, in addition, use controlled burning as a form of land use to burn off fields, value pastures, and thin out fuel loads that could drive uncontrolled fires (Laris, 2002). However, with increased human activities, the intensity and frequency of fires in African savannahs have increased. Overgrazing, shifting cultivation, and charcoal production result in increased burning, habitat degradation and loss of soil fertility through erosion (Savadogo et al., 2007). Repeated burning can transform a savannah ecosystem into a degraded one, with reduced vegetation cover and species composition (Bond & Keeley, 2005). Besides, unregulated fires harm key ecosystem processes such as carbon sequestration, water retention, and biodiversity conservation (Bond & Keeley, 2005). Climate change is altering wildfire behaviour in Africa. Temperature and drought have increased, the savannah biomass is becoming more flammable, and fires have become increasingly intense. Fire plays a significant role in African savannah carbon dynamics, regulating the balance between emissions and carbon sequestration and can transform these environments into carbon sources rather than sinks (Juli G. Pausas & Keeley, 2019).

The Savannah ecological zone of Ghana, an important component of West Africa's diverse landscape, stands at the forefront of environmental change determined by climate dynamics and human activities. This extensive region, characterised by its mixture of grasses, shrubs, and scattered trees, is subject to the complex interplay of wildfire regimes and climate change. Due to the increase in global temperatures and the resulting changes in rainfall patterns, the ecosystem is expected to encounter several difficulties, with wildfires playing a significant part in determining its future (Gajendiran et al., 2024).

Like several West African countries, Ghana is currently experiencing the impacts of global climate change. Over the past decades, the country has witnessed significant shifts in temperature and precipitation patterns. According to the Ghana Meteorological Agency (2020), average temperatures have increased by approximately 1°C since 1960, with projections suggesting a further rise of 1.5°C to 3°C by 2050. Concurrently, rainfall patterns have become increasingly erratic, with more intense precipitation events interspersed with longer dry spells (Asante & Amuakwa-Mensah, 2015). Rapid climatic changes will have profound implications for the Savannah ecosystem, with changes in rainfall patterns affecting vegetation growth cycles, soil moisture content, and water resources. Higher temperatures exacerbate evapotranspiration rates, potentially leading to more frequent and severe droughts (Mondal et al., 2024). A warmer climate and precipitation changes lead to severe fire weather with decreased fuel moisture, increased fuel load, larger burned areas, favourable ignition conditions, a more extended fire season and a greater risk of extreme fire events (Flannigan et al., 2006; Izrael et al., 2007). These situations will not only stress the native flora and fauna but also set the stage for increased wildfire risk worsened by climate change and changing land-use patterns.

Wildfires are a fundamental part of Savannah ecosystems worldwide, playing a crucial role in maintaining biodiversity, nutrient cycling, and vegetation structure (Juli G. Pausas & Keeley, 2019). Historically, fires in Ghana's Savannah occur naturally, with lightning strikes often igniting fires during the transition from dry to wet seasons (Laris et al., 2021). Additionally, anthropogenic fires, used for centuries in traditional land management practices, have shaped the landscape and ecological processes (Archibald et al., 2013). (UNEP, 2022) defined "wildfire" as an unusual or extraordinary free-burning vegetation fire that may be started maliciously, accidentally, or through natural means, negatively influencing social, economic, or environmental values". Fires can become wildfires when they burn out of control, regardless of whether they were started by humans or by nature and how much they help restore the environment (Geographic, 2023).

The Savannah ecosystem fire regime is mainly characterised by its frequency, intensity, seasonality, and spatial extent. These features are intricately linked to climatic conditions, vegetation composition, and human activities (Leys et al., 2019). Under natural conditions, Savannah fires typically occur as low-intensity surface fires, consuming grasses and leaf litter while leaving mature trees largely unscathed (Barnes et al., 2016). Historically, the fire regime in Ghana's Savannah has been very predictable since most of the fires occur during the dry season, typically between November and March. These fires, often initiated by local communities for agricultural clearing, hunting, or pasture management, were generally of low to moderate intensity and played a role in maintaining the open structure of the Savannah (Nyamadzawo et al., 2013).

Wildfires have been occurring within the Savannah ecological zone of Ghana for a very long time. Available records indicate that the country experienced severe bushfires during the catastrophic Sahelian drought (1973-1974) and again in the period 1984-1985, with data indicating that the Guinea and Sudan Savannah areas suffered the most impact with the loss of vegetation, standing crops, farms, wildlife, habitat, human lives, and property (Nsiah-Gyabaah, 1996). In addition, economic, social, and environmental conditions such as agroforestry and land degradation, which affects ecosystem services, are highly triggered by wildfires where thousands of hectares of forests and other lands, including economic trees and other important traditional plant species are destroyed, as well as affecting agricultural productivity in most communities within the savannah ecological zone (Amoako et al., 2018; Kalame, 2009; Yaro & Tsikata, 2013).(E. E. Amoako et al., 2018a)

Climate models project an increase in average temperatures and more frequent extreme weather events, including prolonged droughts and intense rainfall periods (Sylla et al., 2016). These changes will likely create conditions more conducive to fire ignition and spread. The increased temperatures and reduced rainfall during the dry season are anticipated to lead to increased fuel loads of dry vegetation, extending the fire season and potentially increasing fire intensity

(Pausas & Ribeiro, 2013). Conversely, above-average rainfall may promote rapid vegetation growth, fuelling fires in subsequent dry periods. This climate-induced shift in fire regimes poses significant glitches for ecosystem management and fire control strategies. Modifying fire regimes due to climate change is expected to have far-reaching ecological consequences for Ghana's Savannah. More frequent and intense fires can change vegetation structure and composition, potentially favouring fire-adapted species and reducing overall biodiversity (Staver et al., 2011). More sparse vegetation dominated by grasses and shrubs could result from increased tree mortality, particularly among young saplings and fire-sensitive species (Higgins et al., 2007). The cascading effects could be felt in wildlife habitats, changing food webs and species distributions. Moreover, increased fire frequency can impact soil properties, affecting nutrient cycling and potentially leading to soil degradation and erosion (Certini, 2005). The carbon cycle within the Savannah ecosystem is also expected to be disrupted. While Savannahs typically act as carbon sinks, more frequent and intense fires could convert these areas into net carbon sources, contributing to further climate change (Laris et al., 2021).

The wildfire dynamics in Ghana's Savannah have significant socioeconomic implications, mainly when observed through the lens of vulnerability. This susceptibility is exacerbated by the fact that many farmers in the Savannah zone practice rain-fed agriculture, which is already sensitive to weather changes. Crop losses, damage to grazing lands, and the destruction of economically valuable trees like shea (*Vitellaria paradoxa*) and dawadawa (*Parkia biglobosa*) could severely impact food security and income generation (Antwi-Agyei et al., 2018).

Furthermore, the health impacts of increased fire activity cannot be overlooked. More frequent fires lead to deteriorated air quality, potentially increasing respiratory diseases among local populations (Johnston et al., 2012). The economic burden of fire management and suppression will also likely grow, straining already limited resources. Due to economic constraints, this financial pressure can be particularly challenging for local governments and communities with low adaptive capacity. The changing fire regimes also have implications for cultural vulnerability. Many communities in Ghana's Savannah have traditional practices and beliefs tied to the existing ecosystem. Changes in fire patterns and subsequent shifts in vegetation could disrupt these cultural practices, potentially leading to a loss of cultural identity and traditional ecological knowledge (Laris, 2002).

With all these said and done, it is evident that the Savannah ecological zone of Ghana cannot contend with the fires and thus continue to suffer enormous losses in the face of the annual fire events. Research, therefore, is called upon to offer insights into the spatial distribution, frequency, intensity, variability, and seasonal disturbance characteristics of wildfires and what policies could be put in place to tackle them whilst putting in measures for future occurrences.

Firstly, this assessment will help to identify the driving factors, both direct and underlying causes, and impacts of fires contributing to the outbreak of wildfires in the Savannah ecological zone and suggest preventive measures. Secondly, this work examines how fire affects woody species composition, diversity, and vegetation structure in Ghana's Savannah ecosystems: evaluate the effects of wildfire on Savannah ecosystems' structural diversity and vegetation dynamics. Thirdly, an understanding of the nature of the wildfires, their impacts, and the coping and adaptive capacity of affected communities is provided through a vulnerability assessment. This understanding is important in developing appropriate adaptation policies and strategies for wildfire-related climate change. As research in this field continues to evolve, it is crucial to integrate scientific findings with local knowledge and practices to ensure the long-term sustainability of this vital ecosystem and the communities that depend on it. This research provides critical insights into wildfire dynamics, climate adaptation, and ecosystem resilience. It advances fire ecology, remote sensing applications, and biodiversity conservation while offering data-driven solutions for wildfire management, legislation, and climate resilience strategies. The study also informs sustainable land use, community-based fire management, and long-term environmental sustainability in Ghana.

BACKGROUND AND STATEMENT OF PROBLEM

Although fires improve environmental conditions in Savannah ecosystem communities, Wildfires in Ghana's northern Savannah ecological zone have become increasingly frequent and severe due to climate change, posing a significant threat to ecosystem services in the region (Dwomoh & Wimberly, 2017a). These fires disrupt critical ecological processes, impact biodiversity, and affect the livelihoods of local communities that depend on Savannah resources (Kabo-Bah et al., 2019). Recent studies indicate that approximately 30% of Ghana's land area is prone to wildfire, with the Savannah zone particularly vulnerable (GNFS, 2022)Recent estimates based on satellite imagery have shown that depending on the year and the type of vegetation, between 25 and 80 percent of the wooded Savannah burns in West Africa in a year (Laris, 2002). This includes the Savannahs of northern Ghana, as more recently confirmed by global satellite fire products derived from the Moderate Resolution Imaging Spectrometer (MODIS) of Rapid Response System Global Fire Maps (***Figure 1***).

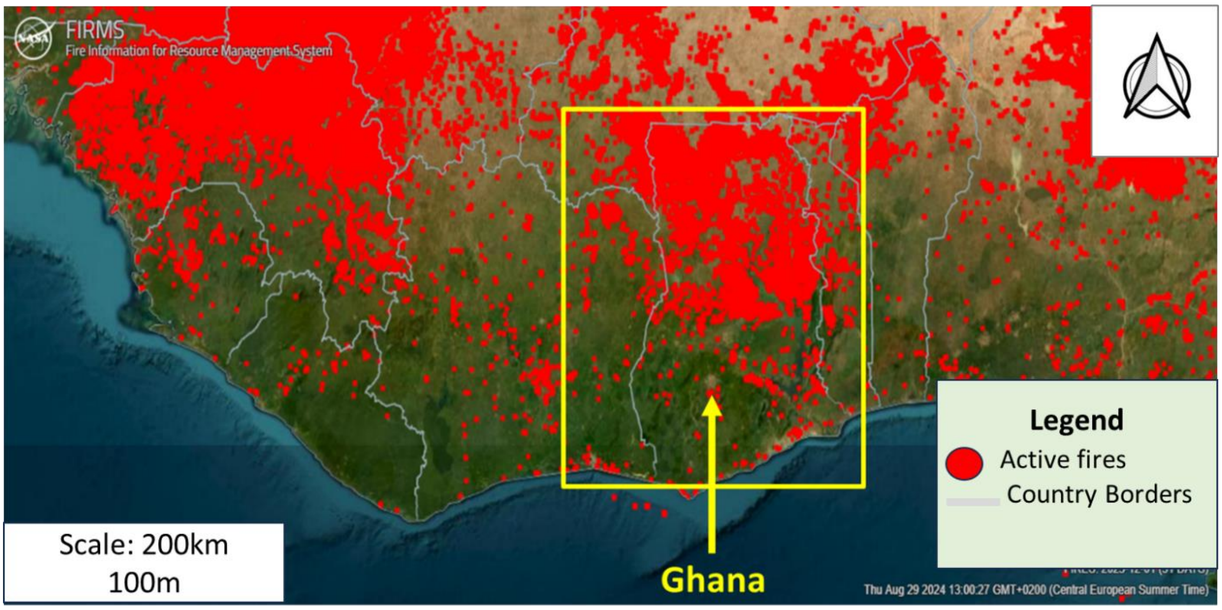

Figure 1: NASA FIRMS. (2024, August 29). Fire detections in West Africa from FIRMS for December 2023 (31 Days) [Satellite map]. NASA Fire Information for Resource Management System (FIRMS). Retrieved from https://firms.modaps.eosdis.nasa.gov

The changing climate has exacerbated this issue, with average temperatures in Ghana rising by 1°C since 1960 and projected to increase by 1.0 - 2.8°C by 2060 (McSweeney et al., 2010). This warming trend and altered precipitation patterns have led to longer dry seasons and increased fuel loads, creating conditions conducive to more frequent and intense wildfires. It is already evident that the Savannahs are at a surge of depletion caused by natural factors such as poor soils and low precipitation (Geist et al., 2006), exacerbated by wildfires with far-reaching consequences across all categories of ecosystems. Several researchers have presented findings on the effects of wildfires on various ecosystems. For instance, Amanor and Pabi (2007) reported a reduced crop yield by up to 40% in wildfire-affected areas. In contrast, Zizka et al. (2015) and Appiah et al. (2010) indicated that medicinal plants and fuel biomass availability decreased by 30% and 25% in frequently burned areas, respectively, under-provisioning services. Moreover, Savannah fires in Ghana potentially release up to 1.5 million tons of CO_2 equivalent annually (Dwomoh & Wimberly, 2017b). Cardoso et al. (2016) noted that biodiversity is severely impacted, with a decrease in tree species richness observed over 20 years in some areas. The impact on tree species in the Savannah zone is particularly concerning. Amissah et al. (2014) found that fire-sensitive species such as *Khaya senegalensis* and *Vitellaria paradoxa* showed a 40-60% reduction in seedling survival rates in areas with frequent fires. Furthermore, (Guuroh et al., 2018) also stipulated that traditional practices tied to specific plant species are threatened, as the availability of culturally significant plants has decreased significantly in frequently burned areas.

In addition to the above, wildfires also severely impact human livelihood. Household incomes from non-timber forest products have declined considerably over the years (Damnyag et al., 2013) and households in fire-prone Savannah areas are more likely to experience food shortages (Codjoe & Owusu, 2011). The underlying fact is that the ecosystem's resilience is being tested. The northern Savannah of Ghana experiences annual fires with less vegetation recovery, and this frequency could lead to a permanent shift from woodland Savannah to grassland, as indicated by (Holdo et al., 2020) and (Issifu et al., 2019) in the ***Figure 2*** below;

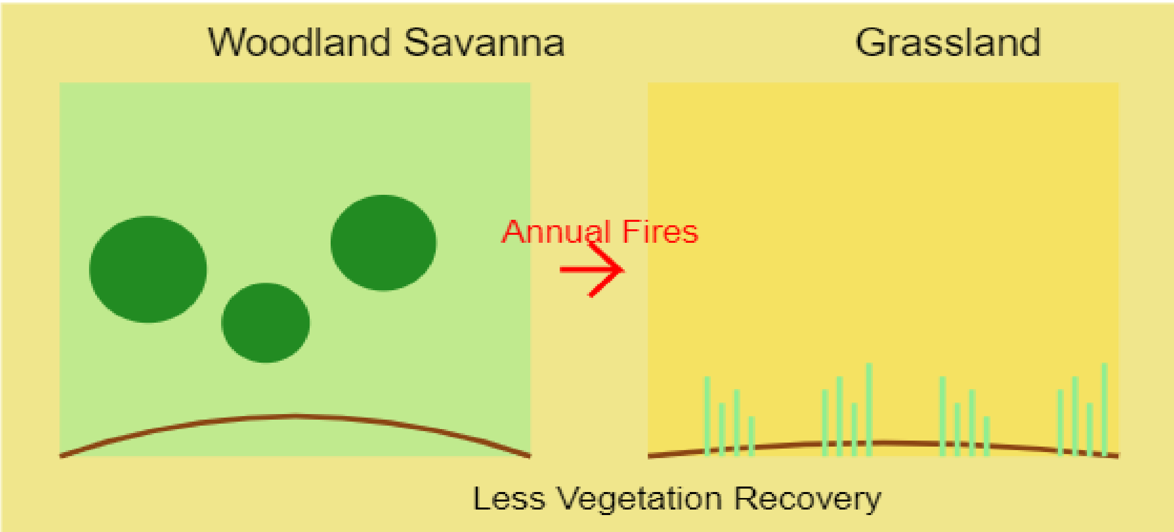

Figure 2: An illustration of the ecological permanent transition from woodland to grassland in the northern savannah of Ghana: adapted from the views of Holdo et al. (2020) and Issifu et al. (2019)

There has been considerable work done on wildfires involving Mediterranean forests (Pausas et al., 2004; Keeley et al., 2011), in the North American prairies (Anderson, 2006; Bowman et al., 2009), and relatively few studies examining the dynamics of wildfires in African savannahs taking climate change into perspective (Archibald et al., 2013; Bond & Zaloumis, 2016).

Despite the significant work done in wildfire studies, poor spatial and temporal analysis is a significant lack of wildfire trends analysis. Most studies on wildfires in Ghana have focused on short-term fires, with less regard for long-term intensity, frequency, and distribution (Guuroh et al., 2018). High-resolution mapping of fires is not yet satisfactory, and it is, therefore, not easy to assess wildfire trends over a duration and between vegetative regions over a period of time. Without spatial technologies, wildfires in uninhabited vegetation will not be captured; therefore, a predisposed prediction may be geared towards the burns around human settlements. With GIS and remote sensing, in this study, wildfire trends in wildfire patterns over two decades (2000–2021) have been examined, including wildfire intensity trends, burning cover, and high wildfire proneness regions, particularly in terms of vegetative change.

Another significant gap is the impact of wildfires on savannah vegetation dynamics in Ghana. While studies have examined the role of fire in vegetation patterns, few have comprehensively analysed its effects on species composition, structural diversity, and long-term vegetation shifts. The extent to which wildfires influence vegetation succession, tree mortality, and the balance between grasses and woody species remains underexplored (Amissah et al., 2014; Dwomoh & Wimberly, 2017a)This work seeks to bridge the gap between wildfire events and vegetation analysis by combining them to provide a complete picture of wildfire contribution in terms of biodiversity, species distribution, and environmental transformations.

Integrating climate change projections into wildfire models is another area that has received insufficient attention. Climate change is a key driver of wildfire, but little work has been performed on projecting future climate change and its contribution to fire regimes and shifts in savannah vegetation in Ghana (Cardoso et al., 2016). In its absence, current policies have been and will remain reactive, not proactive. To bridge such a divide, this work includes climate information in wildfire models to forecast future wildfire danger and shed information about future shifts in fire-dangerous vegetation communities under changing climate scenarios.

The contribution and significance of this study aim to holistically assess wildfire effects on savannah vegetation dynamics in Northern Ghana. It maps wildfire trends and distribution and identifies trends in wildfire evolvement over time, its impact on species diversity, tree dynamics, and landscape composition, and its role in shaping future wildfire regimes under changing climate regimes. The study also develops an integrated practice of fire management that integrates scientific and traditional approaches for effective wildfire suppression and supporting vegetation resilience. By addressing these gaps, this work comes with evidence-based policy and practice recommendations for conservationists, policymakers, and communities for effective wildfire management in savanna environments in Ghana.

RESEARCH QUESTIONS AND OBJECTIVES

This research project aims to comprehensively assess how climate change exacerbated by wildfires affects the savannah ecosystem in northern Ghana. To achieve this aim, the following questions were asked to help achieve the objectives;

1. How do wildfire strategies implemented at the local and national levels influence the resilience of ecosystems?
2. What are the driving factors, direct and underlying causes, and impacts of fires contributing to wildfire outbreaks in the savannah ecological zone?
    a. How do human activities and climatic conditions influence the frequency and severity of wildfires in the savannah ecological zone, and what are their long-term consequences for ecosystem resilience?
    b. To what extent is climate change altering the patterns, intensity, and ecological impacts of wildfires in savannah ecosystems, and how are these changes affecting local communities?
3. How do wildfires affect savannah ecosystems' structural and vegetation dynamics?
    a. How do different fire regimes impact the composition and structure of vegetation in savannah ecosystems?
    b. What role do wildfires play in altering the species diversity and distribution within savannah landscapes?
    c. How vulnerable are species in the savannahs of Northern Ghana to the impacts of wildfires?

RESEARCH OBJECTIVES

1. To systematically review the various wildfire strategies at the local and national level and their relevance to ecosystem resilience.
2. To examine the drivers of wildfires and their impacts on the savannah ecosystem in northern Ghana.
3. To assess the effects of wildfire on savannah ecosystems' structural and vegetation dynamics.

RESEARCH HYPOTHESES

While some aspects of this study involve qualitative analysis, the following hypotheses are formulated for objectives that require empirical validation through data analysis and statistical testing.

1.2.1 Objective 2: Examining the Drivers of Wildfires and Their Impacts

Hypothesis 1: Anthropogenic and Climate Drivers of Wildfires

- **H_{01}:** Human activities (agriculture, land clearing) and climate change (rising temperatures, reduced humidity) do not significantly contribute to wildfire frequency and intensity in northern Ghana.
- **H_{11}:** Human activities and climate change significantly contribute to wildfire frequency and intensity in northern Ghana.

Hypothesis 2: Wildfire Occurrence and Land Use Proximity

- **H_{02}:** Wildfire occurrences are not significantly correlated with proximity to human settlements, agricultural expansion, and land use patterns.
- **H_{12}:** Wildfire occurrences are significantly correlated with proximity to human settlements, agricultural expansion, and land use patterns.

Hypothesis 3: Burned Area Trends and Landscape Variation

- **H_{03}:** There is no significant spatial or temporal variation in burned area trends across different land cover types in the northern savannah zone of Ghana.
- **H_{13}:** There is significant spatial and temporal variation in burned area trends across different land cover types in the northern savannah zone of Ghana.

2.2.1 Objective 3: Assessing the Effects of Wildfire on Ecosystem Structural and Vegetation Dynamics

Hypothesis 1: Fire Regimes and Vegetation Structure

- **H_{01}:** Different fire regimes (low, moderate, high intensity) do not significantly affect species composition and vegetation structure.
- **H_{11}:** Different fire regimes significantly influence species composition and vegetation structure.

Hypothesis 2: Fire Frequency, Tree Cover, and Species Richness

- **H_{02}:** Frequent wildfires do not significantly reduce tree cover or alter species richness in fire-prone areas.
- **H_{12}:** Frequent wildfires reduce tree cover and significantly lower species richness in fire-prone areas.

Hypothesis 3: Fire-Driven Vegetation Changes

- **H_{03}:** Frequent high-intensity wildfires do not significantly alter vegetation structure in fire-prone areas of the northern savannah zone of Ghana.
- **H_{13}:** Frequent high-intensity wildfires promote shrubland expansion and decrease forest cover in fire-prone areas of the northern savannah zone of Ghana.

STRUCTURE OF THE THESIS

This thesis was carried out on a regional scale within Ghana's northern Savannah ecological zone. The thesis is organised into two primary sections, each of which is further divided into distinct segments and presented in the following manner:

This first part of the thesis comprises the ***introductory section*** with a general introduction, the Background/problem statement, the research questions, the study's justification and the thesis's structure. A thesis visualisation was developed detailing how the entire thesis needs to be conducted. ***Chapter One*** also had "The conceptual, theoretical, and review of pertinent literature." The focus was on defining and clarifying relevant concepts concerning wildfires, ecosystem services, climate change, vulnerability, and other relevant concepts for this study. The chapter also describes the study area, location and size, and the climatic characteristics of the study area".

Notably, each Objective was treated as a chapter on its own, from the introduction to the conclusion and references. Hence, Chapters 2, 3 and 4 present the working methods for accomplishing each of the objectives they address. In light of this, the remaining chapters are structured as follows:

Chapter 2: "A review of Wildfire Strategies and Ecosystem Resilience in Ghana's northern savannah ecological zone amidst climate Change". This is a systematic literature review addressing wildfire management strategies.

Chapter 3: "Spatio-Temporal Dynamics, Drivers of Wildfire Occurrence and Distribution in the Northern Savannah Zone of Ghana". It concentrated on addressing the direct and underlying causes of wildfires in the study area.

Chapter 4: Wildfire effects on savannah ecosystems' structural and vegetation dynamics in the north of Ghana: This objective identified Savannah tree species that are resistant to wildfires or on the verge of extinction as a result of wildfire occurrences

Ultimately, the last part comprises a general conclusion and pertinent suggestions derived from the study, references, and appendices, as seen in (***figure 3***) below.

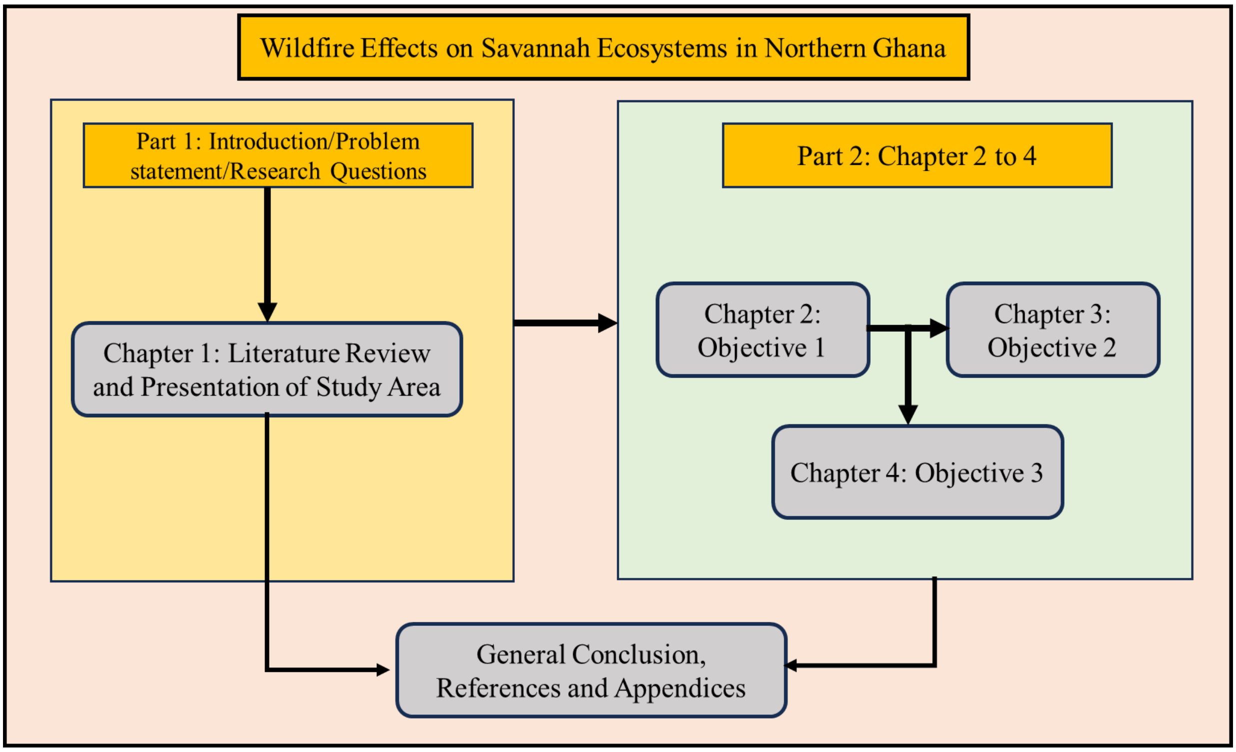

Figure 3: The structure of the thesis shows the interconnectedness of chapters and their relation to the central theme of wildfires in Ghana's Savannah

CHAPTER ONE:

LITERATURE REVIEW AND PRESENTATION OF THE STUDY AREA

This literature review aims to synthesise current knowledge on the effects of wildfires on ecosystems in Ghana's northern savannah. It will explore the complex interactions between fire regimes, ecosystem processes, and the savannah ecosystem. By examining both the ecological and socio-economic dimensions of this topic, this review seeks to provide a comprehensive understanding of the role of fire in shaping ecosystems in Ghana's savannah and identify key knowledge gaps and future research directions.

1.1 Clarification of Key Ecological Concepts in Wildfire and Savannah Ecosystems

Wildfires are a significant ecological phenomenon, defined as uncontrolled fires that spread rapidly across vegetation, often fueled by dry conditions, wind, and flammable materials (Smith et al., 2020). In the context of this study, wildfires refer specifically to natural or human-induced fires occurring in the savannah ecosystem of northern Ghana. These fires are particularly prevalent during the dry season (November to March) and play a dual role in the ecosystem. While they can be destructive, leading to the loss of vegetation and biodiversity, they also promote nutrient cycling and the regeneration of fire-adapted species (van Wilgen, 2025). However, the term "wildfire" is often used interchangeably with "bushfire" or "forest fire," which can create ambiguity. This study focuses on fires within the savannah ecosystem, distinct from other biomes such as forests or wetlands (Jones et al., 2022). Research has shown that anthropogenic activities like farming and hunting and natural factors like lightning primarily drive wildfires in the West African savannah (Sheuyange et al., 2005). Understanding the role of wildfires is critical to assessing their ecological impacts, particularly under changing climatic conditions that may alter fire frequency and intensity.

The ***savannah ecosystem***, the primary focus of this study, is a tropical grassland ecosystem characterised by a mix of grasses and scattered trees with distinct wet and dry seasons (White et al., 1985). This zone comprises the Guinea and Sudan savannah, marked by seasonal rainfall (800–1200 mm annually) and a prolonged dry season, which creates conditions conducive to wildfires. This ecosystem supports diverse flora and fauna, including fire-adapted species such as Andropogon grasses and Acacia trees (Husseini et al., 2020). While "savannah" can refer to various grassland ecosystems globally, this study explicitly examines the Guinea savannah's unique vegetation composition and climatic conditions. Research highlights the role of this ecosystem in supporting livelihoods through agriculture, pastoralism, and non-timber forest products, all of which are influenced by wildfire dynamics (Agyare et al., 2024). The savannah ecological zone thus provides the context for understanding wildfire effects on ecosystems under a changing climate.

The savannah ecosystems are also broadly categorised into **natural savannahs**, maintained by environmental drivers, and **anthropogenic savannahs**, shaped by human activities.

Natural Savannahs emerged in tropical and subtropical regions with seasonal rainfall (800–1,200 mm annually) and distinct wet-dry cycles. They are maintained by periodic wildfires, often ignited by lightning, suppressing woody encroachment and promoting grass dominance (Bond et al., 2005). Key flora, such as fire-adapted *Andropogon* grasses and *Acacia* trees, thrive under these conditions. Natural fire regimes are typically low-intensity surface fires that recycle nutrients and maintain biodiversity (Archibald et al., 2009).

Anthropogenic Savannahs, on the other hand, are the results of human activities, including slash-and-burn agriculture, livestock grazing, and charcoal production, transforming many natural savannahs into anthropogenic landscapes. These practices alter fire regimes, vegetation structure, and soil fertility. For instance, frequent human-lit fires for land clearance often exceed historical fire frequencies, leading to soil degradation and reduced tree cover (Laris, 2002). In West Africa, savannahs dominated by economically valuable species like *Vitellaria paradoxa* (shea) reflect centuries of human management (Luxereau et al., 2012). The intensification of land use pushes savannahs beyond ecological thresholds, leading to irreversible shifts, as reported by Zida et al. (2023), who postulated that charcoal production in Burkina Faso has degraded savannah woodlands into open grasslands.

Natural savannahs are resilient ecosystems shaped by millennia of environmental drivers, whereas anthropogenic savannahs reflect human adaptation and exploitation. In northern Ghana, climate variability, traditional fire use, and modern land-use pressures accentuate the need for integrated management strategies.

Flora, vegetation, and ***species*** are central to understanding ecosystem dynamics in the savannah zone. Flora refers to the plant life occurring in a particular region, while vegetation describes the assemblage of plant species and the ground cover they provide (Levick & Rogers, 2011). Species, defined as groups of organisms capable of interbreeding and producing fertile offspring, play a critical role in ecosystem resilience. In Northern Ghana's savannah, flora includes grasses (e.g., *Andropogon spp*.), shrubs, and trees (e.g., *Acacia spp.*), with vegetation patterns influenced by fire regimes, rainfall, and soil types (Yeboah et al., 2022). Many species in this region have adapted to frequent fires, with some relying on fire for seed germination and growth. However, "flora" and "vegetation" are often used interchangeably, which can lead to uncertainty. For this study, "flora" refers to plant species, while "vegetation" describes their spatial arrangement and structure. Research has documented the resilience of savannah vegetation to fire, with grasses like Andropogon quickly regenerating after burns (Lehmann et al., 2014). Understanding the composition and dynamics of flora, vegetation, and species is essential for assessing the ecological impacts of wildfires and their interactions with climate change.

Abundance and ***dominance*** are fundamental ecological concepts often used interchangeably, yet they have distinct meanings essential for understanding vegetation dynamics in fire-prone ecosystems. In this study, **abundance** refers to the relative number of individuals of a species within a given area, while **dominance** pertains to the extent to which a species exerts ecological control through factors such as biomass, canopy cover, or competitive interactions (Whittaker, 1972; Kent & Coker, 1992). The distinction between these terms is particularly relevant in wildfire ecology, where species composition and vegetation structure are constantly shaped by fire regimes (Bond & Keeley, 2005; Archibald et al., 2018). In savannah ecosystems, frequent wildfires drive species abundance and dominance shifts by selectively favouring fire-adapted species while reducing fire-sensitive ones (Higgins et al., 2007; Lehmann et al., 2014). For instance, in the northern savannahs of Ghana, fire-resistant species such as *Vitellaria paradoxa* and *Parkia biglobosa* may become dominant in burned areas due to their resilience, even if their abundance fluctuates in response to fire frequency (Guuroh et al., 2018; Dwomoh & Wimberly, 2017). Equally, species like *Khaya senegalensis*, which are more vulnerable to fire, may experience a decline in abundance, leading to shifts in the structural composition of the ecosystem (Amissah et al., 2014). Clarifying these terms enhances precision in assessing vegetation resilience and interpreting ecological shifts under changing fire regimes and climate while mitigating ambiguities in ecological research.

Climate change, defined as long-term shifts in temperature, precipitation, and weather patterns, is a critical factor influencing wildfire regimes in Northern Ghana (IPCC, 2021). In this region, climate change is manifested through increased temperatures, erratic rainfall, and prolonged dry seasons, exacerbating wildfire frequency and intensity. These changes have profound implications for ecosystem health and human livelihoods. While "changing climate" is sometimes conflated with short-term weather variability, this study focuses on long-term trends and their ecological impacts. Research indicates that climate change has led to a 20% increase in wildfire frequency in West African savannahs over the past three decades (Mensah et al., 2018). This study explores how changing climatic conditions influence wildfire regimes and ecosystem dynamics in the savannah zone.

Resilience, the ability of an ecosystem to absorb disturbances and recover to its original state or transition to a new stable state, is a key concept in understanding wildfire impacts (Folke, 2006). In the savannah ecosystem of Northern Ghana, resilience is observed in fire-adapted species that regenerate quickly after burns. However, repeated fires and climate change can reduce ecosystem resilience, leading to degradation. While "resilience" is used differently across ecological, social, and economic contexts, this study focuses on environmental resilience. Research has shown that savannah ecosystems with high biodiversity tend to be more resilient to fire disturbances (Nkrumah et al., 2019). Assessing resilience is critical for understanding the long-term impacts of wildfires and developing strategies for ecosystem restoration and conservation.

Disturbance, defined as any event that disrupts ecosystem structure, composition, or function, is a central theme in this study, with wildfires serving as a key disturbance agent (Pickett & White, 1985). Wildfires influence vegetation structure, soil properties, and species composition in the savannah ecological zone. While disturbance can refer to natural events (e.g., fires, droughts) or human activities (e.g., deforestation), this study focuses on wildfires as a natural disturbance. Research highlights the role of fire in maintaining savannah ecosystems by preventing woody encroachment and promoting grass dominance (Bond et al., 2005). Understanding disturbance dynamics is essential for evaluating the ecological impacts of wildfires and their interactions with climate change.

Adaptation, the process by which species or ecosystems adjust to changing environmental conditions, is a key factor in the resilience of savannah ecosystems (Holling, 2013). Flora and fauna have evolved adaptations to frequent fires in the savannah zone, such as fire-resistant bark and fire-stimulated seed germination. While the term can refer to ecological or human adaptation, this study focuses on environmental adaptation. Research has documented fire-adaptive traits in savannah species, such as the ability of Acacia trees to resprout after burns (Gignoux et al., 1997). Understanding adaptation is essential for predicting how ecosystems will respond to changing fire regimes under a changing climate.

1.2. Global Perspective on Wildfires and Ecosystems in African Savannah and Ghana

Globally, wildfires occur roughout the year but with varying burning seasons. Naturally, fires happen more during the driest time of the year, generally at the end of the dry season, while human-induced fires depend on management (Dwyer et al., 2000). Wildfires are a defining ecological process in savannah ecosystems, regulating biodiversity, vegetation structure, and nutrient cycling (Archibald et al., 2018). African savannahs, covering over 50% of the continent's land area, are shaped by fire regimes influenced by climate variability, herbivory, and human activity (Staver et al., 2011; Sankaran et al., 2005). They are characterised by a mixture of grasses and scattered trees and are found in regions with distinct wet and dry seasons. Wildfires have been integral to Savannah ecosystems for millennia, shaping their structure, composition, and function. Central to their ecology is the "fire-vegetation feedback," where fires suppress woody encroachment, maintaining open grasslands (William J. Bond & Keeley, 2005) and also reduce the benefits intended for human beings and other living organisms (MEA, 2005).

Nonetheless, some savannah ecosystems rely on fires, which are a natural part of the environment and necessary to regenerate certain plant species and maintain biodiversity (Archibald et al., 2009). For example, fire-adapted ecosystems like Mediterranean forests, Australian bushlands, and North American prairies depend on periodic fires to sustain their ecological processes (William Bond & Keeley, 2005). Fire plays a central role in shaping the landscape, influencing vegetation patterns, and maintaining grazing land productivity by preventing woody plant encroachment and promoting fire-adapted grasses, which support grazing resources for wildlife and livestock (Yiridoe, Emmanuel & Nanang, 2001). On the other hand, frequent and intense fires, especially those that are human-induced, can lead to soil degradation, loss of vegetation, a decline in the productivity of the land and disruption of water cycles (Flannigan et al., 2000;Savadogo et al., 2007). Also, wildfires significantly affect the storage and regulation of greenhouse gases, such as carbon dioxide, released into the atmosphere when plants are burned (Van Der Werf et al., 2010).

Anthropogenic climate change and land-use intensification disrupt historical fire regimes, leading to more frequent and severe wildfires (Schulte to Bühne et al., 2023). Climate change amplifies fire risk in African savannahs through rising temperatures, prolonged droughts, and delayed rainy seasons (Jolly et al., 2015; Sylla et al., 2016). The IPCC (2021) projects a 30–50% increase in fire risk across sub-Saharan Africa by 2100 under high-emission scenarios, with northern Ghana's transitional climate rendering it acutely vulnerable. Notably, Andela et al. (2017) attribute a 4.3% per-decade rise in West African burned areas since the 1980s to land-use changes. However, their analysis under emphasises localised factors such as Ghana's reliance on fire-based agrarian practices (e.g., slash-and-burn farming), which account for over 90% of wildfires (Amoako & Gambiza, 2022). While this global perspective is well-established, its application to West Africa, mainly northern Ghana, requires greater scrutiny of localised socioecological drivers often overlooked in broader studies. In northern Ghana, the fire season (November–March) coincides with the Harmattan winds, exacerbating fire spread. Fires can destroy crops, reduce forage availability, and lose economically valuable tree species like shea and baobab (Ntibrey et al., 2021). These impacts threaten food security in a region heavily reliant on agriculture and pastoralism.

Ghana's centralised, punitive policies (e.g., the Wildfire Prevention and Management Act, (2018) criminalise unauthorised burning without incentivising community participation (Mirzabaev et al., 2015), unlike southern Africa's community-led fire management or Burkina Faso's integration of traditional "zaï" techniques with early burning (Laris et al., 2021). This approach neglects the dualistic role of fire in savannahs: low-intensity early burns maintain grass dominance and biodiversity, whereas late-season fires degrade soil carbon and reduce tree regeneration (Govender et al., 2006). While Damnyag et al. (2012) and Agyare et al. (2024) document shifts from traditional "shea belt fire" to destructive late-season burns in Ghana. Their work insufficiently addresses how policy failures perpetuate this transition, a critical gap this study seeks to address.

In many African cultures, fire holds profound cultural importance and is a vital landscape management tool. Indigenous communities use controlled burning to clear land for agriculture, enhance pasture quality, and prevent more enormous wildfires (Laris, 2002). Human activity dominates fire dynamics in Ghana's savannahs, driven by slash-and-burn farming, hunting, and land tenure conflicts (Kugbe et al., 2012). These practices, intensified by population growth and agricultural expansion, mirror trends in the Brazilian Cerrado and Australian savannahs, where top-down fire policies clash with Indigenous knowledge (Durigan & Ratter, 2016; Russell-

Smith et al., 2021). Agyare et al. (2024) postulated that there had been a rapid decline of some economic trees, including shea (*Vitellaria paradoxa*) and dawadawa (*Parkia biglobosa*) due to repeated high-intensity fires, highlighting the limitations of global frameworks like REDD+ that prioritise carbon storage over livelihood-linked biodiversity (Acheampong et al., 2021). For instance, Stevens et al. (2017) posit that CO_2-driven woody growth may counterbalance fire-induced "treeless savannahs." However, their model inadequately captures the vulnerability of economically vital species in fire-prone regions like northern Ghana, where ecological thresholds may already be breached.

Emerging climate-fire-vegetation reports threaten to transform savannah structure and function. While Ghana's national strategies lack integration with participatory approaches like Australia's Savannah Burning Projects (Russell-Smith et al., 2021), decentralised "pyrodiversity" principles varying fire timing and intensity could align fire management with local ecological and cultural needs. However, such solutions must address root drivers, including poverty and land tenure insecurity, which are often marginalised in fire ecology literature.

While global studies e.g.,(Bond & Keeley, 2005; Archibald et al., 2018) provide foundational insights into fire-vegetation dynamics, their extrapolation to northern Ghana is limited by three gaps: (1) inadequate consideration of region-specific anthropogenic drivers (e.g., charcoal production, shea parkland dependence); (2) overreliance on climate-centric models that underestimate socio-political barriers to fire governance; and (3) minimal integration of Indigenous fire knowledge, which remains critical for reconciling biodiversity and livelihood goals. Future research must prioritise hyper-local fire regimes and adaptive co-management frameworks to address these disparities.

1.3. Case Studies of Fire Management Successes and Failures in Africa

Several studies have examined the effectiveness of fire management in African savannahs, highlighting both successes and failures. These cases reveal critical lessons for Ghana's northern savannah ecosystems, where wildfires remain a persistent challenge under climate change.

In Zambia, frequent late-dry-season fires in Miombo woodlands resulted in a Community-Based Fire Management (CBFiM) program to train local communities to conduct controlled early burns. These burns, guided by Indigenous fire calendars and satellite monitoring, reduced late-dry-season fires by 40% in Kafue National Park (The Nature Conservancy., 2018; Phiri et al., 2023). This approach stabilised biodiversity and generated community buy-in through carbon credit revenue sharing, illustrating the importance of incentivising participation.

Another success story is recorded in Burkina Faso through its Controlled Early Burning (CEB) strategy, which is rooted in Indigenous Zaï farming practices. This strategy integrates traditional fire timing with weather forecasts to reduce unplanned fires by 60% and enhance crop yields (Laris et al., 2021; Zida et al., 2023). Early dry-season burns are timed to clear grasses while sparing trees critical for agroforestry. However, Burkina Faso's reliance on consistent NGO support contrasts with northern Ghana's fragmented agroforestry systems and intermittent external aid, reflecting broader challenges in scaling participatory fire management where institutional fragmentation persists (Antwi-Agyei et al, 2021). NGOs like "Terre Verte" support communities by combining traditional fire calendars with weather forecasts to optimise burning windows. In the "Centre-Nord" region, this hybrid approach reduced unplanned fires by 60% and boosted crop yields, showcasing how blending ancestral knowledge with scientific inputs can enhance resilience (Zida et al., 2023). Also, the Role of Community-Based Fire Management (CBFiM) in Burkina Faso Community-based fire management has proven effective in Burkina Faso, where local fire brigades manage prescribed burns and firebreaks to protect farmlands and forest resources. Savadogo et al. (2007) showed that integrating local knowledge into fire management strategies significantly reduced fire-induced land degradation

Also, South Africa's Kruger National Park employs adaptive, science-driven fire management using GIS and ecological data to mimic natural fire regimes, curbing invasive species and stabilising woody cover (Govender et al., 2006); (van Wilgen, 2025). This approach underscores the value of flexibility and continuous monitoring in fire management. While this shows the value of flexibility, northern Ghana's limited technical capacity and funding for advanced monitoring tools may require low-cost, community-led adaptations rather than resource-intensive systems, as seen in other West African contexts where participatory mapping has bridged knowledge gaps (Agyare et al., 2024).

Namibia's communal conservancies demonstrate decentralised governance, with local leaders enforcing firebreaks and seasonal bans informed by indigenous knowledge, reducing burned areas by 30% since 2015 (Croker et al., 2023; Thorn et al., 2023)This contrasts with northern Ghana's centralised land governance, where top-down policies often marginalise local fire knowledge. Studies of Ghana's forest-savanna zone critique this pattern, highlighting tensions between statutory and customary land management (Marfo, 2010).

In contrast, Nigeria's Cross River State and Madagascar's Andringitra National Park illustrate the risks of exclusionary policies. Strict fire bans in Nigeria criminalised traditional burns without providing alternatives to slash-and-burn farmers, increasing illegal burning and conflicts (Nkwatoh et al., 2010), while Madagascar's suppression policies disrupted fire-adapted grasslands, exacerbating invasive species (Razafimanantsoa et al., 2025). By banning all fires in highland grasslands, managers inadvertently allowed invasive Aristida grasses to proliferate, which increased fuel loads and fire intensity. The suppression disrupted ecosystems adapted to frequent low-intensity burns, demonstrating that fire exclusion can be as harmful as mismanagement. These cases align with northern Ghana's historical reliance on punitive fire bans, which have similarly neglected livelihood needs and ecological context, a recurring issue in fire management across semi-arid Africa, where policies often prioritise short-term suppression over adaptive, livelihood-integrated strategies (Forsyth, 2013).

Implementing the fire management policy, integrating early warning systems, community involvement, and controlled burning techniques in Botswana reduced wildfire extent while maintaining ecosystem stability (Higgins et al., 2007). The country's strategy demonstrates that well-coordinated fire management can enhance resilience while maintaining ecosystem integrity. On the other hand, Ghana's fragmented institutional frameworks and weak inter-agency coordination may hinder the replication of such cohesive strategies, echoing the critiques of environmental governance in Ghana's climate adaptation programs. The catastrophic wildfires of 1984- 1985 in Ghana burned extensive areas of the savannah, leading to significant losses in crops, livestock, and biodiversity (Nsiah-Gyabaah, 1996). The aftermath revealed weak institutional response mechanisms, a lack of fire prevention education, and inadequate wildfire management policies, emphasising the need for proactive fire management policies. While recent efforts acknowledge the need for community engagement, strategies remain overly centralised and technocratic, overlooking Indigenous fire knowledge, a gap critiqued in studies of Ghana's environmental policy, which emphasises the underutilisation of local ecological knowledge (Nyantakyi-Frimpong et al., 2019). To build resilience, northern Ghana must prioritise decentralised governance, blend traditional and scientific fire practices, and align incentives with local livelihoods. Lessons from Zambia and Burkina Faso are instructive but require adjustments for Ghana's unique socio-ecological dynamics, including erratic NGO support, limited carbon financing, and institutional fragmentation.

1.4. Comparative Analysis with Ghana's Context

Ghana's fire management challenges reflect broader African patterns, blending policies with underfunded governance. Like Nigeria and Madagascar, Ghana enforces restrictive laws such as the Wildfire Prevention Act (2018), which criminalises unauthorised burns but lacks enforcement capacity or community engagement (Mirzabaev et al., 2015; Amoako et al., 2023). This approach has marginalised Indigenous communities whose traditional early-burning practices historically reduced catastrophic fires, a critical oversight in northern Ghana, where anthropogenic fire regimes uniquely shape savannah ecosystems. While Burkina Faso and Zambia demonstrate successes through community incentives (e.g., carbon credits) and hybrid knowledge systems, Ghana's policies remain overly centralised, neglecting localised socioecological dynamics. For instance, studies by (Amoako et al., 2018) inadequately address how northern Ghana's land tenure conflicts and poverty-driven fire reliance complicate blanket bans.

Technological limitations further hinder Ghana's adaptive capacity. Unlike Zambia and South Africa, which deploy GIS and remote sensing for fire prediction, Ghana relies primarily on MODIS data for hotspot mapping (Forkuo & Frimpong, 2012). While MODIS offers broad-scale insights, its coarse resolution fails to capture micro-scale fire dynamics in northern Ghana's fragmented savannahs, a limitation this study critiques, as Sentinel-2's underutilisation undermines localised fire-risk assessments. Namibia's decentralised governance model offers lessons here, yet Ghana's institutional inertia stifles grassroots leadership, perpetuating fire-dependent farming in regions like the Guinea savannah. Persistent funding and governance gaps exacerbate these issues. Ghana's National Disaster Management Organisation (NADMO) struggles with erratic donor support, contrasting sharply with Zambia and South Africa's sustained partnerships and tourism-funded programs (Kugbe et al., 2015). Without addressing structural inequities, Ghana risks replicating Madagascar's policy failures, were rigidity deepened degradation. Critically, existing literature (e.g., Kugbe et al., 2022) overlooks how northern Ghana's agroecological dependencies, such as shea parklands and subsistence cropping, demand context-specific financial mechanisms beyond generic tourism models.

Ghana must prioritise community-led governance to counter wildfire threats, reviving Indigenous early-burning practices through participatory dialogue. Burkina Faso's hybrid knowledge systems integrate traditional calendars with meteorological forecasts, which could reduce late-season fires in northern Ghana while restoring soil health. However, their feasibility requires scrutiny, given the region's erratic rainfall patterns. Adopting Zambia's high-resolution remote sensing tools would enable real-time monitoring, yet challenges like internet connectivity in rural northern Ghana demand pragmatic tech investments. Policy shifts from criminalisation to incentives, such as payments for ecosystem services, must align with local livelihood needs, particularly in fire-prone savannah zones. Finally, addressing root drivers like land tenure insecurity through agroforestry could reduce fire reliance, though existing studies underemphasise northern Ghana's migration-driven land-use pressures.

To conclude, Ghana's fire management stands at a crossroads. By learning from African successes (e.g., Burkina Faso's community partnerships) while avoiding rigid, top-down models, it can tailor solutions to its savannah ecosystems. Northern Ghana's unique socio-ecological context, marked by tenure conflicts, poverty, and climate vulnerability, demands place-based strategies that transcend generic regional frameworks. Integrating indigenous knowledge with adaptive technology, incentivising conservation, and addressing structural inequities could mitigate wildfires while safeguarding biodiversity and livelihoods in a changing climate.

1.5. The Role of Climate Change in Wildfire Dynamics in Northern Ghana's Savannah Zone

Climate change remains one of the most critical factors for wildfire dynamics worldwide, especially in the savannah zone of Northern Ghana. That area is already very prone to wildfires during the dry seasons, and considering further changes to the climate based on rising temperatures, more prolonged droughts, and changed rainfall patterns, the risks for wildfires will continue to increase accordingly (Jolly et al., 2015). IPCC (2021) reported that Northern Ghana, part of the West African Sudanian savannah, faces accelerated warming (2–3°C by 2050 under high emissions) and a 10–20% decline in annual rainfall since the 1970s, delaying vegetation recovery and extending fire-prone periods (Kugbe et al., 2015). Further studies by (Liu et al., 2013) also projected changes in climate by the year 2050, where temperatures may rise by as much as 2.5°C, accompanied by reduced rainfall (Sylla et al., 2016) and droughts (Niang et al., 2014). Such changes could lead to a decline in vegetation moisture and, thus, result in its flammability and effectiveness at sustaining longer fires (Flannigan et al., 2009). Erratic rainfall and long dry seasons in Northern Ghana would further dry the vegetation, thereby increasing the chances of ignition. Intensified Harmattan winds would further desiccate fuels, elevating combustibility (Forkuo & Frimpong, 2012). As a result, the fire season is lengthening beyond what has historically been contained in the dry season, and this is linked to increased temperatures that hasten vegetation drying. The response between wildfires and climate change is particularly concerning for Northern Ghana. Wildfires release significant amounts of carbon dioxide and other greenhouse gases, enhancing the greenhouse effect and accelerating climate change (Bowman et al., 2009). This creates a vicious cycle: as the climate warms, conditions become more favourable for wildfires, releasing more greenhouse gases and perpetuating the cycle. In northern Ghana, this cycle has dire implications for ecosystem resilience and the sustainability of ecosystems and their services. The region's ecosystems, already stressed by human activities such as deforestation and overgrazing, are becoming increasingly vulnerable to the compounded effects of climate change and wildfires. The frequent fires deplete soil organic matter, reduce biodiversity, and degrade land, undermining the region's ability to provide essential ecosystem services, such as food production, water regulation, and carbon storage (Savadogo et al., 2007). As agriculture is the people's primary livelihood, intense and frequent wildfires pose significant stress on crop yields, deteriorate animal grazing lands, and cause a scarcity of water resources, hence impacting people's socio-economic lives. In addition, Elevated CO_2 levels (~420 ppm) theoretically favour woody growth via the "CO_2 fertilisation effect" (William J. Bond & Midgley, 2001). However, this hypothesis overlooks northern Ghana's context, where frequent fires and aridification disproportionately favour fire-adapted grasses over trees (Kugbe et al., 2015).

Climate change exacerbates anthropogenic fire drivers. Declining soil moisture and crop failures push farmers to expand slash-and-burn agriculture, while pastoralists intensify dry-season burning to regenerate pastures (Nkonya et al., 2015). In the Upper East Region of Ghana, climate-linked livelihood insecurity correlates with a 25% rise in fire incidents since 2010 (A. K. Agyare et al., 2024). Nevertheless, these studies often oversimplify human decision-making, neglecting cultural and economic nuances in fire use. For example, prescribed burns for shea parkland management, a traditional practice, are rarely differentiated from uncontrolled wildfires in regional datasets (Naangmenyele et al., 2023). Ghana's climate policies, such as the National Climate Change Policy (NCCP), inadequately address fire risks, prioritising afforestation over fire-climate feedback (Acheampong et al., 2021). This contrasts with Burkina Faso's integrated fire management in climate adaptation (Zida et al., 2023), highlighting

Ghana's policy inertia in leveraging Indigenous fire knowledge, a gap criticised in community-based conservation literature (Chomba et al., 2020).

1.6. Spatial Patterns of Wildfires in the Northern Savannah Zone Using GIS and Remote Sensing

Environmental and anthropogenic factors influence spatial fire patterns in Ghana's savannah. The northern Savannah zone is highly susceptible to wildfires, significantly impacting the region's ecological balance, agricultural productivity, and socio-economic stability. Satellite data analysis has shown that northern Savannah wildfires cluster in specific regions, particularly during the peak dry season. These clusters often correspond to areas of intense agricultural activity, suggesting a strong link between land use practices and fire incidence. (Bajocco & Ricotta, 2008). Integrating Geographic Information Systems (GIS) and remote sensing has significantly advanced our understanding of wildfire dynamics in northern Ghana's savannah ecosystems. These technologies enable the identification of fire hotspots, the analysis of spatial drivers, and the evaluation of ecological impacts, offering actionable insights for adaptive management. Various satellites, such as MODIS (Moderate Resolution Imaging Spectroradiometer) and Landsat, have been widely used to detect fire occurrences, estimate burned areas, and analyse post-fire vegetation recovery (Roy et al., 2008). For instance, MODIS data reveal an annual average of 3–5 major fire hotspots in the Guinea savannah zone, concentrated during the Harmattan season (November–March) when dry winds and low humidity exacerbate fire spread (Forkuo & Frimpong, 2012). Sentinel-2's finer spatial resolution (10–20 m) has illuminated small-scale fires tied to agricultural practices, particularly slash-and-burn farming near settlements like Bolgatanga and Tamale (Dwomoh et al., 2019). However, reliance on MODIS data has limitations: its 1 km resolution often overlooks small, fragmented fires critical to understanding localised ecological impacts in heterogeneous savannah landscapes (Andela et al., 2017). This gap underscores the need for complementary high-resolution datasets, such as UAVs or SAR, to capture fine-scale fire patterns that disproportionately affect tree-grass coexistence dynamics in these ecosystems.

The spatial drivers of wildfires in northern Ghana reflect a complex interplay of anthropogenic and environmental factors. Over 70% of fires occur within 5 km of settlements, roads, and croplands, highlighting human activity as the dominant ignition source (Agyare et al., 2024). For example, fires cluster around Shea parklands and cashew plantations, where farmers use fire for land clearance (Naangmenyele et al., 2023). Land use/cover changes, particularly agricultural expansion, have further intensified fire regimes; a 15% loss of woodland cover in the Upper East Region between 2000 and 2020 corresponded with a 25% rise in burned area (J. Kugbe et al., 2015). While these studies robustly link fires to proximate human activities, they often underemphasise the role of climate-mediated fuel aridity and historical fire legacies in shaping contemporary fire susceptibility. For instance, (Agyare & Danso, 2016) attribute fire clustering near settlements solely to human ignition but overlook feedbacks where prior burns create fragmented landscapes that are more flammable and attractive to encroachment—a critical gap for savannah ecosystems where fire-vegetation feedbacks dictate long-term resilience (Adekunle et al., 2012).

Post-fire ecological impacts, assessed through remote sensing indices like NDVI and EVI, reveal reduced ecosystem resilience in frequently burned areas. In Mole National Park, annually burned sites exhibit 30–40% slower NDVI recovery compared to areas with two to three-year fire intervals (Dwomoh & Wimberly, 2017a). Landsat imagery further shows that recurrent fires reduce tree canopy cover by 10–15% per decade, favouring invasive species (Adekunle et al., 2012). However, such studies often conflate fire frequency with severity, neglecting how fire timing (e.g., early vs. late dry season) mediates ecological outcomes. For example, fires late in the dry season likely cause more significant tree mortality due to lower fuel moisture, a nuance rarely captured by annual NDVI trends alone (Agyekum et al., 2024).

Research on persistent fire corridors, such as those in Bawku-West District and Sissala East Municipality, illustrate region-specific drivers like cross-border pastoralism and slash-and-burn cashew farming (Agyekum et al., 2024). While these spatially explicit analyses are valuable, their reliance on satellite imagery often sidelines local ecological knowledge. For example, fires near sacred groves in Lawra District, documented through participatory mapping (Agana et al., 2018), highlight how community-driven data can refine satellite-based models that otherwise miss culturally mediated fire practices.

Fire risk models using machine learning algorithms, such as MaxEnt and Random Forest, demonstrate high predictive accuracy but frequently exclude socio-economic variables like land tenure systems that influence fire use (Forkuo & Frimpong, 2012). This omission risks oversimplifying fire management in regions where communal grazing lands and degraded woodlands are disproportionately vulnerable due to institutional, not just ecological, factors.

While GIS and remote sensing have revolutionised fire monitoring in northern Ghana, their application remains constrained by technical and conceptual limitations. MODIS's coarse resolution and cloud cover challenges during the Harmattan season hinder precise fire detection, necessitating hybrid approaches integrating SAR and VIIRS (Andela et al., 2017). Furthermore, studies emphasising anthropogenic drivers often overlook responses between fire regimes and climate change, such as prolonged droughts altering fuel availability, a critical concern for savannahs under projected warming (IPCC, 2021).

In addition, policy strategies, such as Ghana's zoning for high-risk areas, must balance satellite-derived fire susceptibility maps with ground-truthed community insights. For instance, targeting savannah-woodland ecotones for firebreak construction (Kugbe et al., 2015) could be enhanced by incorporating Indigenous fire management practices that maintain biodiversity (Agana et al., 2018). Moving forward, interdisciplinary collaboration and community co-production of data will be essential to address gaps in current spatial analyses and foster resilient fire management frameworks.

THEORETICAL FRAMEWORKS

1.7. Theoretical Lenses for Analyzing Wildfire Effects on Ghana's Savannah Ecosystem.

The study of wildfire effects on Ghana's northern savannah ecosystem can be understood through several theoretical lenses. This section explores various theoretical frameworks that provide the foundation for analysing the complex interactions between fire, ecosystems, and human societies. Specifically, the review focuses on Socio-Ecological Systems Theory, Disturbance Ecology Theory, Climate Change and Fire Regime Theory, Fire Ecology Theory, Succession Theory, Ecosystem Services Framework, and Resilience Theory. By synthesising insights from these theories, this review aims to provide a comprehensive understanding of the multifaceted impacts of wildfires on Savannah's ecological dynamics and the ecosystems they support.

Socio-Ecological Systems Theory

The Social-Ecological Systems (SES) theory, developed by Elinor Ostrom and colleagues, provides a framework for understanding the complex interactions between human societies and natural ecosystems (Ostrom, 2009). This theory posits that social and ecological systems are inextricably linked and should be studied as a unified system. Socio-Ecological Systems (SES)

Theory offers a holistic framework for understanding the interdependence between human societies and ecosystems. In the background of Ghana's northern Savannah, the SES framework aids in understanding how human fire use practices, land management decisions, and socioeconomic factors interact with ecological processes to shape fire regimes and ecosystems. It also examines how fire regime changes might affect the system's environmental and social components. Traditional fire management practices in the Savannah of Ghana are often rooted in indigenous knowledge and coexist with national fire policies (Amanor & Pabi, 2007; Kull, 2002). Socio-Ecological Systems (SES) Theory provides a framework to analyse how these multi-level strategies interact and their relevance to ecosystem resilience (Ostrom, 2009).

While Amanor and Pabi (2007) and Kull (2002) provide valuable insights into traditional fire practices, their analyses often underplay the accelerating socio-environmental shifts disrupting these systems, such as climate-induced aridification and expanding agricultural frontiers (Naangmenyele et al., 2023; Nkonya et al., 2015). Also, studies like Kull (2002) frame indigenous fire knowledge as static, overlooking its adaptive capacity in the face of contemporary pressures like erratic rainfall and land fragmentation. This oversight risks romanticising traditional practices without addressing their evolving efficacy under modern stressors. Similarly, national fire policies are often critiqued as top-down in SES literature (Kojo S. Amanor & Pabi, 2007) and are rarely evaluated for their unintended consequences, such as displacing controlled burns that historically maintained Savannah's biodiversity (Laris, 2002) (Kouassi et al., 2022). Furthermore, SES applications in this context seldom engage with power asymmetries influencing fire governance. For example, gender and class disparities in resource access can skew fire management outcomes, yet these dimensions remain peripheral in mainstream SES analyses (Saito-Jensen et al., 2010).

The SES diagram (***Figure 4***) conceptualizes the interplay between social, economic, and political settings and ecological subsystems in shaping fire-related outcomes. The ***ecological subsystem*** encompasses processes such as tree growth, nutrient cycling, and biodiversity, all critical to savannah ecosystems, where fire regimes directly influence vegetation structure and soil fertility (Mbow et al., 2014). Fire suppression policies, often advocated by national governance systems, can disrupt natural nutrient cycling by allowing excessive biomass accumulation, increasing the risk of catastrophic wildfires (Laris, 2002). Controlled burning is common in savannah and is intended to prevent large, uncontrollable wildfires (Laris, 2002; Wardell et al., 2004). However, the effectiveness of such practices in promoting long-term resilience of ecosystem services, such as soil fertility and biodiversity, remains a critical area of inquiry (Nyantakyi-Frimpong, 2020; Sankaran et al., 2005). SES Theory also highlights the role of social institutions in shaping ecological outcomes. Studies have shown that when aligned with environmental knowledge, community-based fire management practices can enhance the resilience of ecosystems and services (Walters, 2017; Acheampong et al., 2021). Fire in Ghana is both a cultural tool and an ecological force. Socio-Ecological Systems (SES) Theory helps in understanding how cultural practices, economic needs, and environmental imperatives intersect to influence fire regimes and their impact on ecosystem services (Adom, 2018; Owusu-Ofori et al., 2021; Nyantakyi-Frimpong et al., 2019).

Meanwhile, the ***governance system*** comprising local governments, regional boards, and policies reflects the multi-scale governance challenges in northern Ghana, where state-led fire bans frequently clash with indigenous fire management practices (Kojo S. Amanor & Pabi, 2007). ***Resource units*** such as trees, vegetation, and fauna are both shaped by fire regimes. In Ghana's Savannah, fire-dependent species like *Vitellaria paradoxa* (shea tree) rely on low-intensity burns for regeneration. However, overharvesting and land conversion increasingly decouple these ecological relationships (Nkonya et al., 2015). The forest actors, such as landowners, households, hunters, and firefighters, highlight the role of human agency in fire dynamics. Smallholder farmers often use fire for land clearance, a practice embedded in local livelihoods but increasingly contested due to climate-driven aridity (Naangmenyele et al., 2023). Interactions such as information exchange, harvesting, and conflict resolution are pivotal. Indigenous fire knowledge, transmitted through generations, traditionally balanced ecological needs with agricultural demands (Angassa, 2014). However, the diagram's portrayal of "equity" in interactions glosses over power imbalances. For instance, gender disparities in land ownership often exclude women from fire management decisions, exacerbating unsustainable practices (Saito-Jensen et al., 2010). Similarly, lobbying by commercial agro-industries (absent in the diagram's actors) skews fire policies toward suppression, neglecting traditional fire-foraging systems that maintain biodiversity (Kull, 2002). ***Outcomes*** related to ecosystems, such as altered fire regimes, are often framed neutrally in SES models. Yet, rigid fire bans in northern Ghana have led to paradoxically worse ecological outcomes, including invasive species encroachment and reduced grassland diversity (Mbow et al., 2015). This underlines a critical gap in SES applications.

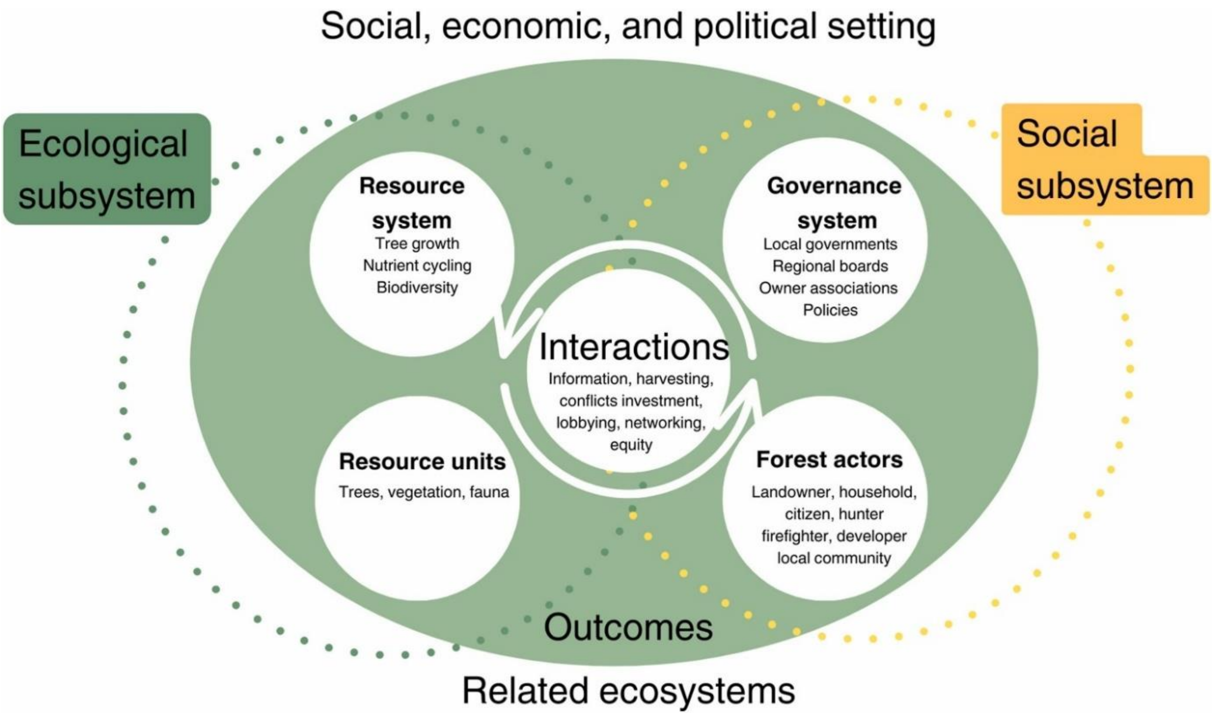

Figure 4: Conceptualization of forests as a social-ecological system with examples of each group of variables, adapted from Ekström et al. (2024), Ostrom, (2009) and with inspiration from McGinnis and Ostrom, (2014)

The key aspects of SES theory relevant to this study include:

Interdependence: Recognizing the system's mutual dependence between social and ecological components. How do the actions of local communities, such as land use, agricultural practices, and fire management strategies, directly influence the health and functioning of the ecosystem?

Feedback loops: Understanding how changes in one part of the system can affect other parts through complex feedback mechanisms. For example, frequent wildfires can change vegetation structure, altering local climate conditions, soil fertility, and biodiversity.

Resilience: Examining the system's capacity to absorb disturbances and maintain its essential structure and function. How can the ecosystem and the communities that depend on it withstand the impacts of wildfires without losing their ability to provide critical services?

Adaptive management: Emphasizing the importance of flexible, learning-based approaches to ecosystem management. Given the unpredictable and evolving nature of wildfires and their impacts, adaptive management involves continuously monitoring and adjusting management practices based on new information and changing conditions.

These aspects of SES theory provide a robust framework for understanding and addressing the complex challenges of wildfires in Ghana's northern Savannah. They guide the research in exploring the intricate relationships between human and ecological systems and developing strategies that promote environmental sustainability and social well-being.

Climate Change and Fire Regime Theory

While Pausas and Keeley (2009) and Flannigan et al. (2009) argue that climate change directly drives increased fire frequency and intensity globally, this perspective may oversimplify the dynamics in West African savannahs. In northern Ghana, fire regimes are strongly influenced by anthropogenic activities (e.g., slash-and-burn agriculture, hunting, and charcoal production) rather than purely climatic factors (Laris, 2002; Agyare et al., 2016). For instance, Kugbe et al. (2012) acknowledge climate impacts but underplay the role of socio-economic drivers like population growth and land-use changes, which are critical in shaping regional fire patterns. Similarly, Archibald et al. (2013) global models of climate-fire interactions may lack resolution for localised savannah systems where human ignition dominates fire regimes (Dwomoh & Wimberly, 2017a). This gap suggests a need to integrate socio-ecological frameworks into climate-fire theory for African savannahs.

Disturbance Ecology Theory

Pickett & White (1985) and Sousa (1984) established that disturbances like fire maintain biodiversity, but their universal application to northern Ghana's savannahs requires scrutiny. Studies such as Higgins et al. (2007) and Smit et al. (2010) emphasise fire-induced reductions in woody cover, yet this may not fully apply to fire-adapted savannahs where certain woody species (e.g., *Vitellaria paradoxa*) thrive under moderate fire regimes (Savadogo et al., 2007). Furthermore, Bowman et al. (2009) focus on fire intensity and overlook the importance of fire timing (e.g., early dry-season vs. late dry-season burns), which critically determines ecological outcomes in West Africa (Andersen, 2021). For example, late-season fires in northern Ghana often coincide with harmattan winds, exacerbating soil degradation and reducing grassland resilience, a distinction absent in broader disturbance theory (Armah et al., 2011).

Many studies (e.g., (Amoako et al., 2018; van Wilgen, 2025) generalises fire impacts on savannahs without accounting for northern Ghana's unique ecological and cultural context.

Traditional land management practices in the savannah shape fire regimes, such as rotational burning by local communities to maintain soil fertility and control pests (Zida et al., 2023). Also, climate change projections (e.g., prolonged droughts) may interact with existing land fragmentation, altering fire spread and recovery dynamics in ways not captured by global models. Dwomoh and Wimberly (2017b) provide a rare regional exception, linking fire recurrence to land-cover changes in Ghana. However, their work lacks empirical data on belowground carbon or microbial responses to fire.

The assumption that fire universally enhances biodiversity (Bowman et al., 2009) conflicts with evidence from northern Ghana, where excessive anthropogenic fires reduce native grass diversity and promote invasive species. Similarly, Turner's (2010) framework for ecosystem resilience does not account for the compounding effects of overgrazing and fire, which synergistically degrade savannahs in the Sahelian zone (Hiernaux, 2020). This highlights the need for theories addressing multiple disturbances in socio-ecological systems.

Fire Ecology Theory and Succession Theory

Fire Ecology Theory posits that fire is a natural ecological process shaping savannah ecosystems (Bond & Keeley, 2005). While this theory provides a foundational understanding of fire-adapted flora and fauna, its universal application to regions like northern Ghana warrants scrutiny. Much of the foundational research, such as Sankaran et al. (2005), derives from southern or eastern African savannahs, where climatic conditions, soil types, and fire regimes differ significantly from West Africa's Sudanian savannahs (Furley, 1999). Northern Ghana's highly weathered, nutrient-poor soils may constrain post-fire nutrient cycling and vegetation recovery, challenging assumptions about rapid resilience (Anderson, 2006). Similarly, Hoffmann et al. (2012) emphasise fire-resistant traits like thick bark. However, in northern Ghana, smallholder agricultural practices (e.g., slash-and-burn) alter fire intensity and frequency, potentially selecting different adaptive strategies (Amoah & Addoah, 2021). This underscores the need for region-specific studies, as global models (Archibald et al., 2013) often overlook localised anthropogenic drivers.

Succession Theory, which describes post-disturbance recovery (Connell & Slatyer, 1977), faces similar limitations in northern Ghana. While Coop et al. (2020) suggest that frequent fires suppress tree establishment, this dynamic may be exacerbated in West Africa by prolonged human land use (e.g., grazing, farming), which disrupts natural succession pathways (Laris, 2002). For example, traditional fire management in northern Ghana often timed to clear land for crops reduces grass biomass critical for fuel continuity, creating fragmented burns that alter vegetation recovery (Kugbe et al., 2022). Such practices diverge from the "natural" fire regimes assumed in Succession Theory, leading to savannahs dominated by fire-tolerant shrubs rather than grasses or trees (Mbow et al., 2015). This mismatch highlights the theory's limited integration of socioecological feedback, a gap increasingly recognised in fire ecology (Bowman et al., 2020).

Critically, Fire Ecology and Succession Theories often neglect the role of soil moisture in mediating fire impacts. In northern Ghana, short rainy seasons and prolonged droughts (Abdul-Razak & Kruse, 2017) may reduce post-fire recovery rates compared to mesic savannahs, contradicting assumptions of rapid resilience (Stevens et al., 2017). Ryan and Williams (2011) note that soil moisture thresholds influence fire-induced tree mortality, yet such thresholds remain unquantified in West Africa. Similarly, human-driven fires during the dry season may exacerbate soil degradation, further limiting succession (Nelson, 2022). These gaps underscore the need to contextualise global theories with local data, particularly where anthropogenic pressures intersect with climatic stressors (Addoah et al., 2023).

Resilience Theory

Resilience Theory emphasises the capacity of ecosystems to absorb disturbances while maintaining their functions and services (Folke, 2006; Holling, 2013). In wildfire research, this theory frames savannah ecosystems' ability to recover from fire events and sustain essential services (Anderies et al., 2013). While this perspective is valuable, critics argue that its application often overlooks localised socioecological dynamics in West African savannahs, particularly the interplay of fire regimes with anthropogenic pressures like grazing, agriculture, and fuelwood extraction (Laris, 2002). For instance, studies in northern Ghana highlight that frequent fires, prolonged droughts, and land-use changes can reduce grass biomass and alter soil nutrient cycling, processes inadequately captured by generalised resilience frameworks (Agyare et al., 2017).

Resilience theory also posits thresholds beyond which ecosystems shift to alternative states (Walker & Salt, 2006). However, this assumes uniform responses to fire disturbances, whereas northern Ghana's savannahs exhibit heterogeneous recovery patterns due to variability in soil types, species composition, and human interventions (Dwomoh & Wimberly, 2017b; Furley et al., 2008). For example, fire-adapted species like Andropogon gayanus may dominate post-fire recovery in some areas, masking the underlying degradation of biodiversity (Mistry, 2000). Such nuances challenge the theory's predictive capacity in fragmented landscapes. Furthermore, resilience frameworks prioritise ecological metrics (e.g., vegetation regrowth) over socioecological feedback critical to human livelihoods. In northern Ghana, where communities rely on fire for land clearance and pasture management, resilience is co-determined by adaptive governance and local knowledge (Kugbe et al., 2012; Zida et al., 2023). Nevertheless, many resilience studies neglect institutional weaknesses (e.g., weak enforcement of fire bans) that exacerbate ecosystem vulnerability. This gap underscores the need for integrative models that address both ecological thresholds and socio-political drivers of fire regimes.

1.8. PRESENTATION OF THE STUDY AREA

1.8.1. Introduction

Ghana's northern Savannah ecological zone is chosen as the study area because it faces several environmental challenges. These challenges threaten the region's ecosystem health and human livelihood (Antwi et al., 2014). The region is also the most agricultural part of Ghana, with a high percentage of subsistence food crop farmers and a rural poverty incidence of about 52%. The incidence and severity of fire events in the northern savannah zone have risen over the years due to human activities coupled with climate change and variability, worsening the stability of the ecological system and local communities. (Asante & Siaw, 2019). This chapter describes the study area regarding the research objective: the effects of wildfires on ecosystems. It describes the area's physical, socio-economic, and environmental conditions and how they influence wildfires.

1.8.2. Location of the Study Area

The Northern Savannah Ecological Zone of Ghana, a region of important ecological importance, lies within latitudes 8°N and 11°N and longitudes 0°W and 2°W at the northern end of the country. The West African region occupies about 40% of Ghana’s total land size and has a geographic size of 97 704 square kilometres; it is bounded to the north by Burkina Faso, in the east by Togo and the south by the transitional forest zone of Ghana. The western boundary of the zone Ivory Coast. Some administrative towns within the study area are Tamale, Bolgatanga, Wa, Damongo, and Nalerigu. These serve as regional capitals to the Northern, Upper East, Upper West, Savannah, and North-East regions. The proximity of the Northern Savannah to the Sahel region is also very susceptible to desertification, which is progressing today (Asante & Siaw, 2019). ***Figure 5*** below shows the geographic location of the study area, which shows the five main regions in Northern Ghana.

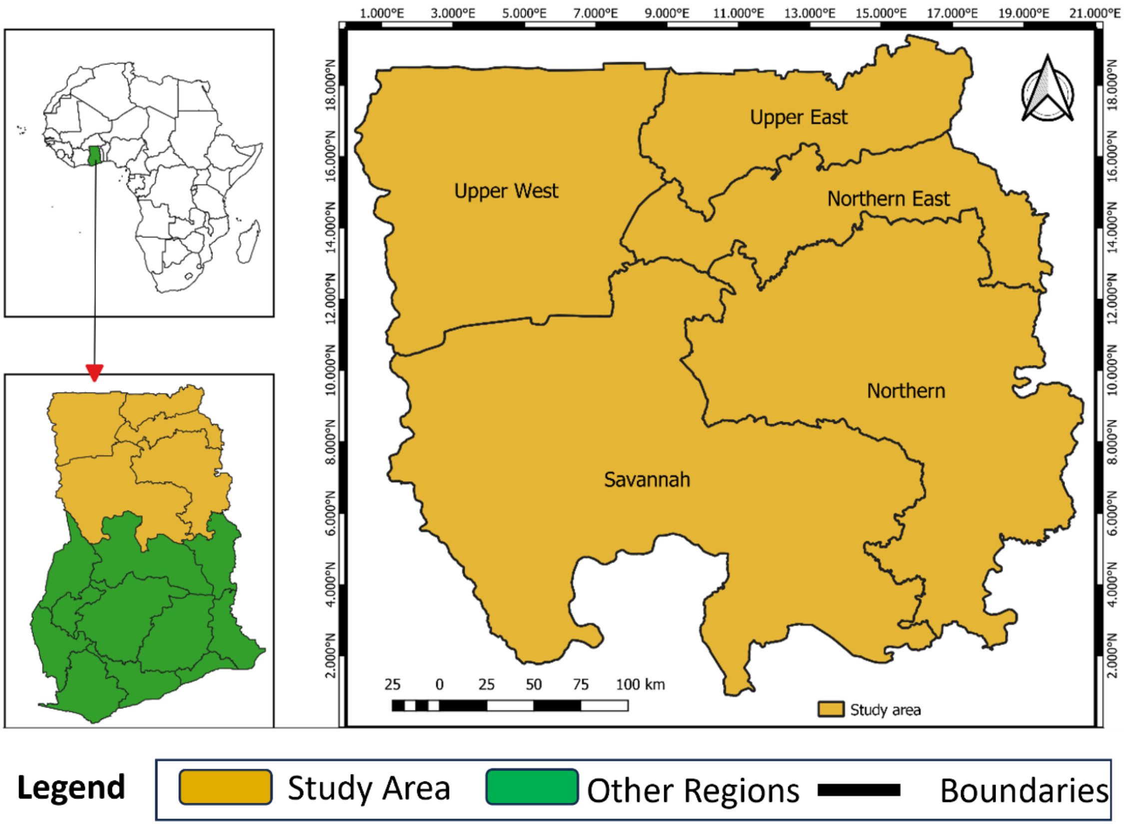

Figure 5: Map of the study area (Source: Self-constructed using GIS data from Ghana Statistical Service, 2024).

The ***Northern region*** is the largest in the country, covering a land area of about 70,384 km^2. Wildfires have become rampant in the region, primarily during the dry season from November to March, due to the vegetation being savannah, which consists of grasslands and scattered trees, providing much fuel for fires. The ***Upper West Region*** of Ghana is located in the northwest and occupies an area of about 18,476 square kilometres. This region is prone to fires due to a long dry season and open terrain. The rate of wildfires is high due to the production of charcoal during the dry season. The literature review reported that fires in the upper west region blazed through the grassland and impacted the rural and urban populace (Mensah et al., 2018). ***The Upper East Region*** is located in northeastern Ghana and has about 8842km^2 in total land size. The Region records some of the highest incidences of wildfire in Northern Ghana. Due to the hot and dry climate and frequent agricultural and pastoral activities, the region has intentional fire occurrences. The ***Savannah Region*** is situated west of the Northern Region and has a land size of 35,862 square kilometres. Although fires are less common compared to other areas of the study area, they can be intense due to the expansive grasslands and savannah woodlands around the area. Fires often start with hunting or accidental bushfires, affecting nearby protected areas such as Mole National Park (Agyare & Danso, 2016). The ***North-East region*** occupies a total land area of approximately 9,072 square kilometres. The area's geography has rocky slopes that make firefighting very challenging. Wildfire incidents have intensified in this region due to the expansion of agricultural land and deforestation (W. Asante & Siaw, 2019). The area is mainly rural, with scattered settlements and agriculture as the dominant economic activity. Agricultural practices, such as slash-and-burn farming, dry conditions, and harmattan winds, significantly facilitate the rapid spread of fires in all regions.

Major roads in the Northern Savannah Ecological Zone of Ghana are important regarding transport and wildfire management. The main ones are the Tamale-Bolgatanga Highway, Wa-Tamale Road, and Bolgatanga-Bawku Road. They provide significant firebreaks that, when properly developed, reduce the speed of or make the spread of wildfires impossible (Agyemang et al., 2017). These roads are cleared on either side, providing a physical barrier that eliminates the continuity that the flammable vegetation enjoys during the dry season. Some of these roads pass primarily through regions prone to wildfires from farming and charcoal-burning activities, but they also provide critical access for firefighting teams, enhancing emergency response times (Mensah et al., 2018). In addition, some of these roads, such as the Fufulso-Sawla route that cuts across Mole National Park, contribute to safeguarding sensitive ecological areas by serving as barriers between wildfires and forest reserves(Safo, 2016). The Eastern Corridor Road has improved the situation of wildfire management due to better access to the fire-prone zone, besides serving strategic barriers in agricultural areas (Owusu & Waylen, 2009). Overall, in this region, roads serve as a crucial infrastructure for transportation and reduction of wildfires to lower the possibilities of large-scale fire hazards in communities, agricultural lands, and natural ecosystems.

The Northern Savannah Ecological Zone in Ghana has witnessed several devastating fire incidents in the last decade, and these have helped reduce the region's environmental productivity and capacity to support livelihoods. In 1983, a major wildfire event occurred in Ghana, and this has often been used as an important reference point that pointed to the fact that the north savannah is very much prone to fire outbreaks (Safo, 2016; Asante & Siaw, 2019). These fires affected large parts of the Northern, Upper East, and Upper West regions, burning crops, trees, and animals. Many people lost their properties, including food produce and farms, reducing the food factor significantly. Mensah et al. (2018) also identified that their large-scale fire incidences in parts of the Upper West Region, affecting towns around, destroyed several hectares of farmland and forest areas. It was also reported that thousands of farmers lost their crops, emphasising maize and millet, essential food crops. Forest reserves were also affected, leading to a loss of biodiversity and habitat destruction. The fire season of 2019 - 2020 was characterised by more frequent bushfires in the Northern, Upper East, and North-East regions. Many fire incidents occurred in Bolgatanga and surrounding areas during this period, damaging crops, properties and natural resources. According to Asante & Siaw (2019), the fires were cited to have resulted mostly from human-influenced activities like shifting cultivation and facilitated by low humidity conditions that characterised the Harmattan period. GNA, (2022) also reported that in January 2022, the country's Northeast region experienced a series of fire outbreaks that razed over 500 hectares of farmlands and vegetation. These fires were said to be caused by dry conditions that persisted for many months and farming activities that destroyed the food production in the regions. These disasters represent recurrent and rising regular wildfire events in Northern Ghana caused by human actions and climate factors.

1.8.3. Biophysical characteristics

Rivers and water Bodies:

The terrain is dominated by the Volta River Basin, which includes the Black Volta, White Volta, and Oti Rivers and their tributaries (Yeboah et al., 2022). Fires around the White Volta Basin are most dangerous due to their effects on riparian areas and water sources, a matter of concern that requires urgent rectification (Safo, 2016). These rivers are critical for agricultural irrigation, drinking water, and hydroelectricity production. They also include riverine forests, which act as fire barriers when encroaching on the riverbanks. Nevertheless, with low water levels and sandy soils during the dry season, such areas become vulnerable to fire spread following the drying up of vegetation in riverine zones (Asante & Siaw, 2019).

Geology and Topography

The geology dramatically influences the physical and ecological features of the Northern Savannah Zone (NSZ), hence determining the pattern and frequency of wildfire events. Geological structures in NSZ, including the weathering of granitoids and sandstones from the Birimian Supergroup and Voltaian Basin, greatly determine the sandy and loamy soils. These soils are often shallow, containing less organic matter and are prone to erosion (Safo, 2016). Due to high incidences of lithosols in much of the Northern Savannah region, the grass species that dominate this ecological region are characterised by high flammability, especially during the dry season biomass production (Agyemang et al., 2017). Continuous wildfires will destroy the vegetative cover and further degrade these soils. The topography is undulating, with steep slopes affecting drainage patterns and influencing fire behaviour. Fires tend to spread more rapidly on slopes due to wind patterns and the nature of fuel accumulation on these slopes. Studies have shown that steep terrain can cause fires to intensify and spread faster than in flat areas (Mensah et al., 2018).

Climate

Ghana's Northern Savannah Ecological Zone has a distinct tropical savannah climate characterised by one rainy season and a long dry season. This climate pattern explains the wildfire dynamics, agricultural production and food security, and conservation status of the region. The zone experiences a unimodal rainfall distribution, with the start of the rainy season usually in late April and ends early November. This area has an estimated mean annual precipitation ranging between 900 mm and 1,200 mm, with the maximum precipitation occurring in July and August (K Owusu & Waylen, 2013). Possible future climate scenarios for the Sahel region. There is also regional variation in rainfall distribution, with areas around Bolgatanga having a lean season longer than most areas in the Tamale and Damongo parts of the zone. The climate in the study area is primarily semi-arid and controlled by two distinct air masses: the hot, dry, and dusty North-East Trade Winds (Harmattan), which initiate from the Sahara Desert, and the cold and moist South-West Monsoon winds, which blow from the south from the Atlantic Ocean (Incoom et al., 2020). The dry season extends from November to March, during which the region is dominated by the dry, northeasterly Harmattan winds, which blow from the Sahara Desert. These winds bring dry, dusty air, lowering humidity levels and creating conditions conducive to the rapid spread of wildfires (Asante & Siaw, 2019). During this period, temperatures can soar above 40°C in the hottest months (February and March), while humidity levels can drop as low as 10% to 20%. The Harmattan season is critical in influencing the frequency and intensity of wildfires, as it dries out grasses and other vegetation, creating large amounts of highly flammable biomass. The onset of the rains rejuvenates the region's grasslands and woodlands, providing much-needed moisture after the long dry season. However, due to climate variability, the reliability of rainfall has become increasingly unpredictable, leading to periods of drought that further exacerbate fire risks (Safo, 2016).

The mean average temperature in the zone ranges from 28°C to 32°C but can be extremely high at 42°C during the dry season, especially in February and March (Asante & Siaw, 2019). During the rainy season, temperatures are moderate but relatively warm. The dry season, characterised by high temperature but low humidity density, makes the region especially prone to fires due to the accumulation of highly combustible material such as dry vegetation (Owusu et al., 2014). In addition, evapotranspiration increases in high temperatures, which creates a high deficit of moisture in the soil and increases the vulnerability of fire in savannah systems. The area has received less regular rainfall and has been characterised by delayed onset of the rainy season and shorter rainfall duration. This has affected rainfall duration and intensity, as well as frequent and severe heat waves, which have been established to increase the incidences of wildfires (Agyemang et al., 2017). In addition, the length of the dry season has extended, leading to enhanced wildfire incidence and frequency and more damage to both natural and agricultural resources. These climatic changes directly implicate the resilience of local ecosystems and communities, such as farming and livestock rearing, which are typically concerned with the usual climatic cycles.

1.8.4. Vegetation and Ecosystem Characteristics

The Northern Savannah Zone of Ghana is characterised by grasslands and extensive open woods with scattered trees (as seen in ***Figure 6***) below and could be regarded as one of the most sensitive ecological zones in terms of natural resource exploitation and the most sensitive ecological zone due to susceptibility to various harmful human activities and environmental stress factors. The climatic conditions, geological features, and human land-use practices shape the vegetation and ecosystems in this region. The region comprises two major savannah zones, the Guinea Savannah and the Sudan Savannah, with different vegetation cover systems and functions.

The Guinea Savannah zone, the more extensive of the two savannah types, occupies the Northern, Savannah, and North-Eastern zones. Open woodlands are dominant in this zone, and these include shea (*Vitellaria paradoxa*), baobab (*Adansonia digitata*), African locust bean (*Parkia biglobosa*), and acacias. Tropical grasses such as *Andropogon gayanus, Hyparrhenia ssp*, and *Pennisetum ssp* are also common. These grasses thrive well during the rainy season, especially during the warmer periods, hence accelerating and dying off by the beginning of the long dry season, leading to fuel accumulation and the easy ignition of wildfires (Safo, 2016).

Figure 6: Savannah vegetation captured in Lawra Faalu: Source; Field survey, 2024

The Guinea Savannah woodlands provide important ecosystem services such as carbon sequestration, soil fertility, and habitat for wildlife. The Sudan Savannah zone, comprising the Upper East and Upper West regions, is drier and more sparsely vegetated than the Guinea Savannah. Short-grazed grasslands and low tree density characterise this zone, with the most typical trees being brittle acacia (*Acacia sieberiana*) and baobabs (*Adansonia digitata*). The trees are primarily isolated with patchy coverage, giving a low density for the canopy. Different grasses grow prolifically in the region and are characterised by a smear of green during the rainy season and dry out in the dry season. The vegetation in the Sudan Savannah is comparatively dry and hence vulnerable to fire danger, as the grasses are inflammable, and trees are few (Agyemang et al., 2017). Fire is a natural part of this ecosystem, helping to maintain the grassland structure by preventing the encroachment of trees.

The (table 1) below provides a summary of some of the characteristics of the study area;

Table 1. Summary of Characteristics of the Study Area

Characteristics	***Savannah Ecological zone***
Climate	Semi-Arid
Rainfall patterns	Mono-modal
Major Rainfall period	April to November
Annual Average Rainfall	1250-1750 mm
Monthly Average Temperature	27°C and 36 °C
Soil Types	Savannah ochrosols
Hydrology	Black Volta, White Volta
Vegetation	Grasses/shrubs
Socio-economic activities	Agriculture, shea butter processing, hunting

1.8.5. Socioeconomic Characteristics

Population Size and Growth

The 2021 Ghana population and Housing census indicates that the population of the Northern Savannah ecological zone is now over six (6) million (GSS, 2021). The largest population is in the Northern Region, with Tamale as one of the main cities, and the other four regions have comparatively small populations. The people from this area are ethnically diversified and include the Dagomba, Mamprusi, Gonja, and Mossi. The population growth rate in this zone remains somewhat higher than the average for the country due to high birth rates and a relatively young population. Increasing population density in the area threatens natural resources and agricultural expansion at the cost of cutting down trees, which, in turn, raises wildfire likelihood. The Zone is youthful, and more than 40% of the people residing in the area are below 15 (GSS, 2021). The youthful demographic also means a large proportion of the population is economically dependent, placing significant stress on household resources, agriculture, and employment opportunities.

The zone is predominantly rural, with more than 70% of the population depending on farming, animal rearing and other natural resource-related activities (GSS, 2021). Urban centres such as Tamale, Bolgatanga, Wa, Damongo, and Nalerigu are gross but have a relatively small population share. The rural nature of the zone means that the population is predominantly rural and depends enormously on land for Agriculture activities and charcoal burning, which triggers acts that lead to fire outbreaks.

Notably, the Northern Savannah zone has lower coefficients in education and literacy than the national level. The education level in the region is relatively low compared to Ghana's total percentage literacy rate, which is over 70% (GSS, 2021). Low education standards affect the failure to practice new and improved farming methods, fire management, and environmental conservation. This can indirectly affect fire regimes because many rural populations utilise traditional land management practices, including fires.

Agriculture and Livelihoods

Agriculture is the primary livelihood for the vast majority of the population in the Northern Savannah Ecological Zone of Ghana, which includes the Northern, Upper East, Upper West, Savannah, and North-East regions. The region’s rural economy relies heavily on subsistence farming and livestock rearing, with limited access to irrigation and modern agricultural technologies. Rain-fed Agriculture is the most practised in all five regions, with the crops being produced during the unimodal rainy season of May up to October. Maize, millet, sorghum and groundnuts are staple foods in all the regions. However, yields are closely associated with the onset and frequency of rainfall. The nature of rainfall in the Northern Savannah region is mainly seasonal, consequently limiting farming because, due to dry spells and erratic rain, crop yields have been impaired, thereby deepening poverty. Slash-and-burn farming is common in all five regions, which results in dry-season wildfires. Livestock farming is also practised in the NSZ, and pastures are often burned to promote their regrowth, increasing the risk of uncontrolled fires. Producing charcoal and cutting firewood are everyday economic activities that help degrade vegetation and expose the area to fires.

1.9. CONTRIBUTIONS OF ORGANIZATIONS AND INSTITUTIONS TO WILDFIRE PREVENTION IN THE NORTHERN SAVANNAH ECOLOGICAL ZONE

Several organisations and institutions, both governmental and non-governmental, have recognised the severity of wildfire issues in the region and are actively engaged in fire prevention, management, and mitigation efforts. Their contributions are crucial in reducing the incidence of wildfires, protecting ecosystems, and safeguarding livelihoods in the affected regions.

The National Disaster Management Organisation (NADMO) is the leading governmental institution in charge of disaster management in Ghana. One of its key roles in the Northern Savannah Ecological Zone is preventing and managing wildfires. To enhance public awareness of NADMO and wildfire issues, NADMO engages the Local Assemblies, Traditional Authorities, and Communities in Public Education Campaigns, especially in rural areas, on the causes of wildfires, especially during farming activities. Furthermore, NADMO works with the various district assemblies to mobilise and train community fire volunteers whose duty is to help identify and prevent fires. These teams are vital in preventing fire outbreaks from escalating and causing havoc in the dry season (NADMO, 2020).

The Ghana National Fire Service (GNFS) is the primary government agency responsible for preventing and combating fires. While a core mandate of GNFS is central and urban fire prevention, they have expanded their operations to reach rural regions of the Northern Savannah zone due to escalating wildfires. GNFS's contributions, for example, include firefighting training for community members on prevention and control of fire, particularly in areas where people engage in bush burning for agriculture practices. They also involve farmers and members of the community in the use of suitable and recommendable techniques of soil preparation in order to discourage the use of fire. The GNFS also features fire outbreak surveillance and assists local governments in attending to numerous reported wildfires. However, due to scarcity and fixed access in remote regions, GNFS is always delayed in responding to wildfire incidents (GNFS, 2022).

The Ghana Environmental Protection Agency (EPA) plays a significant role in protecting the environment and preventing wildfires. According to the EPA, the NSZ deals with the sustainable use of land, conserving ecosystems, and the effects of fires on the environment. The EPA strongly encourages the introduction and application of rules for controlling fire usage in arable and land management practices. It also works with other government departments to enforce fire-related environmental legislation and punish persons whose actions lead to more uncontrolled fires.

The Forestry Commission manages the country's forest resources and ensures sustainable use. The government has developed strategies to prevent reoccurring fire occurrences in and around forest reserves through the Forestry Commission. The Forestry Commission has implemented programs to reduce the incidence of wildfires in and around forest reserves. This involves working with local communities to establish firebreaks and strips of cleared land that help prevent fire spread into forested areas. The Commission encourages the establishment of Community Resource Management Areas (CREMAs), where local communities are responsible for managing and protecting forests and other natural resources. Some of this management involves avoiding fire risks and applying principles of proper land use to prevent fire disasters from affecting forests (Commission, Forestry, 2019).

1.9.1. Non-Governmental Organizations (NGOs)

Several NGOs, such as CARE International, World Vision International Ghana and Friends of the Earth Ghana, are involved in the Northern Savannah Ecological Zone's wildfire prevention and environmental protection efforts. These organisations promote sustainable farming practices, fire management, and reforestation. In addition to local efforts, international organisations such as the Food and Agriculture Organization (FAO) and the United Nations Development Programme (UNDP) provided support in suppressing fire incidences and its management zone by promoting sustainable land management practices that reduce fire risks, such as agroforestry and soil conservation techniques and also supported projects aimed at increasing resilience to climate change impacts, including wildfires, by promoting climate-smart agriculture and sustainable fire management practices (FAO), 2018; UNDP, 2019).

1.9.2. Traditional Authorities and Local Governments

Traditional authorities, such as chiefs and elders, play a pivotal role in wildfire prevention in the NSZ. These authorities are often responsible for enforcing local bylaws that regulate fire use in farming and other land management activities. In many communities, chiefs have established seasonal fire bans to prevent uncontrolled fires during the most vulnerable periods, typically the late dry season. Traditional authorities work closely with local governments to ensure these bans are respected and offenders are penalised (Asante & Siaw, 2019).

The contributions of various organisations and institutions to wildfire prevention in the NSZ have been vital in reducing the frequency and intensity of wildfires. Through public education, community engagement, policy enforcement, and sustainable land management practices, these organisations are working to protect the region's ecosystems and livelihoods from the destructive impacts of uncontrolled fires. However, ongoing challenges such as resource limitations, climate change, and widespread traditional practices mean that continued efforts are necessary to effectively address wildfire risks in the zone.

CHAPTER TWO:

A SYSTEMATIC REVIEW OF THE VARIOUS WILDFIRE STRATEGIES AT THE LOCAL AND NATIONAL LEVELS AND THEIR RELEVANCE TO SAVANNAH ECOSYSTEM RESILIENCE.

Part of it was published in a journal and can be read on this link: https://www.researchgate.net/publication/381788888_Wildfire_Management_Strategies_and_Ecosystem_Resilience_in_Ghana's_Savannahh_Ecological_Zone_Amidst_Climate_Change_A_Systematic_Review_of_Literature

2. Abstract

This systematic literature review examines wildfire management strategies and their implications for ecosystem resilience in Ghana's Savannah ecological zone, with particular attention to the effects of climate change. The review employed a structured search strategy across multiple academic databases, including Google Scholar, Scopus, and Web of Science, covering publications from 1985 to 2023. 371 studies were initially retrieved based on predefined inclusion and exclusion criteria, with 85 selected for in-depth analysis. Three categories of wildfire management strategies were identified: community-based efforts, policy and regulatory frameworks, and technology interventions. The findings highlighted the predominance of community-based wildfire prevention measures, integrating indigenous knowledge and participatory governance structures. Policy interventions, although well-documented, often lack enforcement and coordination among institutions. Technological approaches such as GIS and remote sensing have significantly improved fire monitoring and early warning systems but remain underutilised locally. The review stressed the complex interplay between natural and anthropogenic fire regimes, challenging the binary classification of wildfires as either beneficial or destructive. This study identified critical gaps, including inadequate community engagement in policy-making, limited data on long-term fire trends, and the need for integrated fire management frameworks. Addressing these gaps requires a multi-stakeholder approach, combining local knowledge with scientific advancements in fire prediction and mitigation. The findings will provide a foundation for future research and inform more effective wildfire management policies to enhance ecosystem resilience in Ghana's Savannah ecological zone.

Key Words: Wildfire management, ecosystem resilience, Savannah, climate change, Ghana

2.2. INTRODUCTION

Wildfires pose a multifaceted threat to ecosystems and human communities worldwide. Globally, wildfires have been intensifying in frequency and severity, fueled by climate change, land-use changes, and human activities (Dahan & Kasei, 2022). The World Health Organization (WHO, 2021) characterises wildfires as unintentional burns that destroy natural areas like meadows and forests. While wildfires have historically sustained savanna vegetation, shaping ecosystem structure and composition over millions of years (Bond, 2019; Niema et al., 2021; Archibald et al., 2017), the predominant scientific perspective views them as detrimental to ecological integrity, necessitating urgent study and intervention (Valea & Ballouche, 2012; Aubréville, 1949)

In Africa, the savannah ecological zones of West Africa are particularly susceptible to wildfires, with their frequency exacerbated by dramatic climatic shifts (FAO, 2018). Most of these fires are anthropogenic, ignited by pastoralists to promote regrowth or initiated near settlements and protected areas to mitigate larger-scale fires and reduce total burned areas (Anane & Antwi-Agyei, 2021; Dwomoh & Wimberly, 2017). The effects of wildfires in this region extend beyond environmental degradation to economic and social impacts, affecting agriculture, biodiversity, and air quality.

In Ghana, wildfires present a persistent challenge across its diverse ecological zones, including forests, transition areas, and savannahs (Sackey & Hale. (2008). The FAO's 2010 assessment indicates Ghana has one of the highest rates of vegetation loss due to wildfires. In particular, Ghana's savannah ecological zone is particularly vulnerable, as highlighted in the 2020 Nationally Determined Contributions (NDC) report. Despite the historical presence of fire as a natural ecological regulator, its increasing severity and frequency demand enhanced management efforts. Various fire management strategies have evolved, particularly in protected areas, encompassing community-based fire management, public awareness campaigns, research and monitoring, and early warning systems (Anane & Antwi-Agyei, 2021; Baker et al., 2018; Archibald et al., 2018; Van Wilgen, 2013). Nevertheless, a comprehensive understanding of the efficacy, challenges, and prospects of wildfire prevention, mitigation, and management strategies in Ghana's savannah remains elusive.

Given this context, it is imperative to critically examine wildfire strategies and ecosystem resilience in Ghana's savannah for sustainable environmental management. The current systematic literature review aims to synthesise and analyse existing knowledge, providing insights into wildfire strategies and their implications for ecosystem resilience. By assessing the historical context of wildfires, identifying management strategies, and evaluating ecosystem adaptability and resilience in response to climate change, this review seeks to illuminate the complex interactions between wildfires, climate change, and ecosystem resilience in Ghana's savanna ecological zone.

2.3. BACKGROUND- THE IMPACT OF CLIMATE CHANGE ON THE SAVANNAH ZONE OF NORTHERN GHANA

Globally, the impacts of climate change are particularly pronounced in vulnerable developing nations, with Ghana experiencing rising temperatures, declining rainfall, increased variability, rising sea levels, and more frequent extreme weather events and disasters (Minia , 2004). The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as "a change of climate attributed directly or indirectly to human activities that alter the composition of the global atmosphere, in addition to the natural climate variability observed over comparable periods" (UNFCC, 2011). In Ghana, vulnerability to climate change encompasses exposure to floods, droughts, sea erosion, and temperature increases, affecting people, environments, and sectors differently based on their vulnerability levels.

In the Savannah ecological zone, climate change drives extreme weather events like flooding, high temperatures, and shifts in rainfall patterns pose significant challenges. The Ghana National Climate Change Adaptation Strategy (N.C.C.A.S.) notes rising temperatures across the nation, including the Savannah ecological zones, where higher-than-average temperature trends have been recorded. Historical data indicate shifting precipitation patterns, with more irregular and unpredictable rainfall, extended dry periods, and intense rainfall events (Abbam et al., 2018). These climatic changes heighten the frequency and intensity of wildfires by creating prolonged dry conditions and increasing vegetation flammability. As temperatures rise and humidity levels decline, dried grasses and shrubs become highly combustible, accelerating wildfire spread once ignited. The Savannah ecological zones, with their vast expanses of grasslands and scattered trees, are particularly prone to rapid wildfire spread due to the abundance of fine fuels such as dry grasses and leaf litter (Arko-Adjei et al., 2009). Climate-induced changes, such as prolonged droughts, intensify these conditions, making ignition more likely and facilitating rapid fire spread. Additionally, strong winds common during the dry season further exacerbate fire propagation, leading to widespread ecological and socio-economic consequences (Wasserman & Mueller, 2023).

Climate change interacts with human-induced fire drivers to amplify wildfire risks. Land clearance for agriculture, including slash-and-burn practices, is a significant ignition source, often leading to uncontrolled fires that spread beyond intended boundaries. Deforestation for agricultural expansion and fuelwood collection further alters the landscape, reducing canopy cover and exposing more flammable vegetation layers (Amogu et al., 2010). These factors, combined with climate-induced stressors, result in increased fire frequencies and intensities across the savannah

The ecological consequences of climate-driven wildfires threaten biodiversity, habitat loss and landscape fragmentation, affecting the survival of various species (Tessema et al., 2021). Changes in fire regimes also influence vegetation composition, reducing tree cover and favouring fire-tolerant species while eliminating fire-sensitive species. Over time, these shifts alter ecosystem structure and function, affecting carbon sequestration potential and exacerbating land degradation (Laris et al., 2015).

Climate change significantly affects human livelihoods. Changes in precipitation patterns and increased temperatures affect crop suitability, while unpredictable weather disrupts traditional farming practices, impacting food security (Onyeaka et al., 2024). These disruptions, food shortages, and increased vulnerability to climate change impacts increase community vulnerability, particularly among subsistence farmers who depend on natural resources for survival (Amogu et al., 2010).

Previously, Ghana's wildfire management and climate adaptation efforts were largely reactive, focusing on post-fire interventions. However, there is a growing recognition of the need for proactive mitigation strategies. Government policies promoting sustainable land management, fire prevention education, reforestation initiatives, and climate-resilient agricultural practices are essential for enhancing ecosystem resilience (Republic of Ghana, 2016). Integrating climate-smart policies into national development planning can help reduce wildfire risks while ensuring long-term sustainability for ecosystems and livelihoods in the savannah.

2.3.1. Review Objective and Questions

This systematic literature review examines existing wildfire strategies in Ghana’s Savannah ecological zones. It assesses the current state of ecosystem resilience against wildfire strategies, the impacts of climate change on these strategies, and ecosystem resilience. It also examines wildfire policies and legislation within the Savannah ecological zone of Ghana. The following questions guided these objectives;

1. What wildfire strategies (legislations and policies) are implemented in Ghana's Savannah ecological zone?
2. How does climate change impact wildfire management strategies, and what policy regulations are in place to address the challenges posed by evolving climatic conditions?
3. What is the current state of ecosystem resilience in response to wildfires in Ghana's Savannah ecological zone?
4. How effective are wildfire management and prevention strategies in Ghana's Savannah ecological zone, and what improvements are needed to enhance their impact?

2.4. METHODOLOGY AND RESULTS

The methodology for this systematic literature review on wildfire strategies and ecosystem resilience in the Savannah ecological zones was structured around the Preferred Reporting Items of Systematic Reviews and Meta-analysis (P.R.I.S.M.A.) guidelines developed by (Moher et al., 2014). PRISMA ensures transparency, reproducibility, and comprehensiveness in literature synthesis. The framework has been widely applied in environmental science and policy reviews, as demonstrated by (Haddaway et al., 2015) and (Pullin & Stewart, 2006), who examined ecosystem resilience and climate adaptation strategies. A systematic literature review was chosen for its structured approach to synthesising existing knowledge. This method enables a thorough assessment of wildfire strategies, their effectiveness, and their impact on ecosystem services. The theoretical foundation aligns with the evidence synthesis methodologies (Gough et al., 2019) proposed, emphasising systematic reviews as essential for policy and decision-making in environmental research.

2.4.1. Inclusion and Exclusion Criteria

A comprehensive search strategy was employed across multiple electronic databases, including Scopus, Google Scholar, online African journals, the International Journal of Wildland Fire and specialised journals focusing on wildfires and ecosystem resilience, as shown in (*Table 2*) below. These databases were selected based on their credibility and coverage of peer-reviewed wildfire management and ecosystem resilience research. The search focused on peer-reviewed articles, government reports, and case studies published between 1985 and 2024. This period was selected based on (1) the increasing prominence of wildfire management policies after the severe 1983–1984 Ghanaian bushfires, (2) the advancement of satellite-based fire monitoring in the early 2000s, and (3) the growing global integration of climate change adaptation strategies in wildfire governance post-2015 (Paris Agreement).

The search criteria included peer-reviewed journal articles, policy documents, and legislative texts on wildfire management and ecosystem resilience, focusing on Ghana’s Savannah ecological zone and relevant comparisons from West Africa. Studies discussing climate change impacts, community-based fire management strategies, and biodiversity resilience were prioritized. Excluded sources included non-peer-reviewed studies, research outside the specified geographical scope, and paid publications without institutional access. The search utilised keywords and Boolean operators such as "wildfire strategy", "wildfire management", "wildfire implications", "fire prevention", "community involvement in wildfire", "wildfire policy", "wildfire legislation", "climate change mitigations and adaptation", "ecosystem resilience", “ecological adaptations”, “biodiversity resilience”, “vegetation dynamics”, “Ghana Savannah”, and “wildfire management” in west Africa.

These words were relevant to the review’s topic without restricting the publication date to include historical literature. This approach was broadened to encompass studies on Savannah ecosystems in Ghana and other West African sub-regions, showcasing the diversity of strategies across different Savannah ecosystems. The review was limited to peer-reviewed publications. The inclusion and exclusion criteria were meticulously applied to ensure that only relevant studies were considered for analysis

Table 2. Database and search engines that were searched in the review

Database and search engine	**Link**
UDSspace University for development studies online database	http://udsspace.uds.edu.gh/bitstream
K.N.U.S.T. Space Kwame Nkrumah University of Science and Technology online database	https://ir.knust.edu.gh/home
U.G. Space, university of Ghana online database	https://ugspace.ug.edu.gh/bitstream
U.C.C. Institutional Repository, University of Cape Coast	https://ir.ucc.edu.gh/
Google Scholar	https://scholar.google.com/
African journals online	https://www.ajol.info/index.php/ajol
Scopus	Scopus preview - Scopus - Welcome to Scopus
International Journal of Wildland Fire	https://www.iawfonline.org/international-journal-wildland-fire-ijwf/

2.4.2. Articles Published

***Figure** 7* shows articles reviewed based on the inclusion and exclusion criteria. The figure represents the number of articles published over a series of years, from 1985 to 2025. From 1985 to 2005, a low and almost constant number of articles were published; generally, about one article per year reflects minimal research efforts during this period. Starting from 2010, there was a slight increase in the publication of articles, reflecting a gradual rise in research interest or output. There was a significant increase around 2015, peaking at 7; the number of articles reflects that more academic output came out or was article-incentivized around this year regarding the topic. After the peak, the number of articles fluctuated with a few yearly drops, but a significant increase reappeared around 2023.

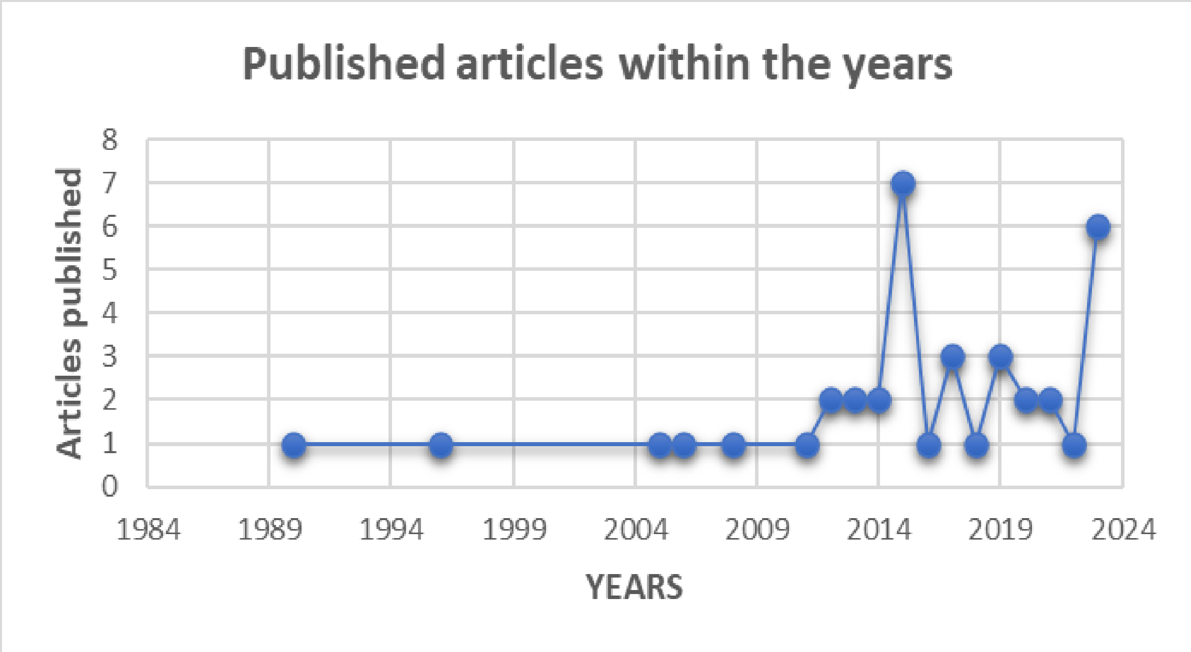

Figure 7: The number of published articles on wildfire management between 1985 and 2025 over the years that met the inclusion and exclusion criteria

2.4.3. Selection of Studies

The identification, screening, eligibility assessment, and inclusion of studies followed a structured approach, as illustrated in (***Figure 8***). **371** articles, publications, policies, and regulations were initially retrieved from multiple academic databases and institutional repositories, including UDS Space (42), UG Space (11), UCCIR (5), KNUST Space (8), Google Scholar (181), AJOL (43), and SCOPUS (81). To eliminate redundancy, **92** duplicate records were removed before screening.

279 records were assessed based on their titles and abstracts during the screening phase. **194** records were excluded based on several criteria: irrelevance to wildfire strategy (e.g., focusing instead on fire disaster management strategy), lack of relation to the Savannah ecological zone, non-relevance to ecosystem resilience or climate change, and inability to access the full text due to paywalls. **85** full-text articles were eligible and reviewed for relevance. Of these, **31** studies were excluded due to full text not being available (paid access), studies not focused on the key themes of the review, and not being published in English. After applying the eligibility criteria, **54** studies were included in the final analysis.

This rigorous assessment ensured that only the most relevant and accessible materials were included in the review. The extracted information was then carefully analysed, and the findings were presented clearly and comprehensively to ensure transparency and adherence to recognised academic and research standards, as (seen in ***Figure 8)*** below.

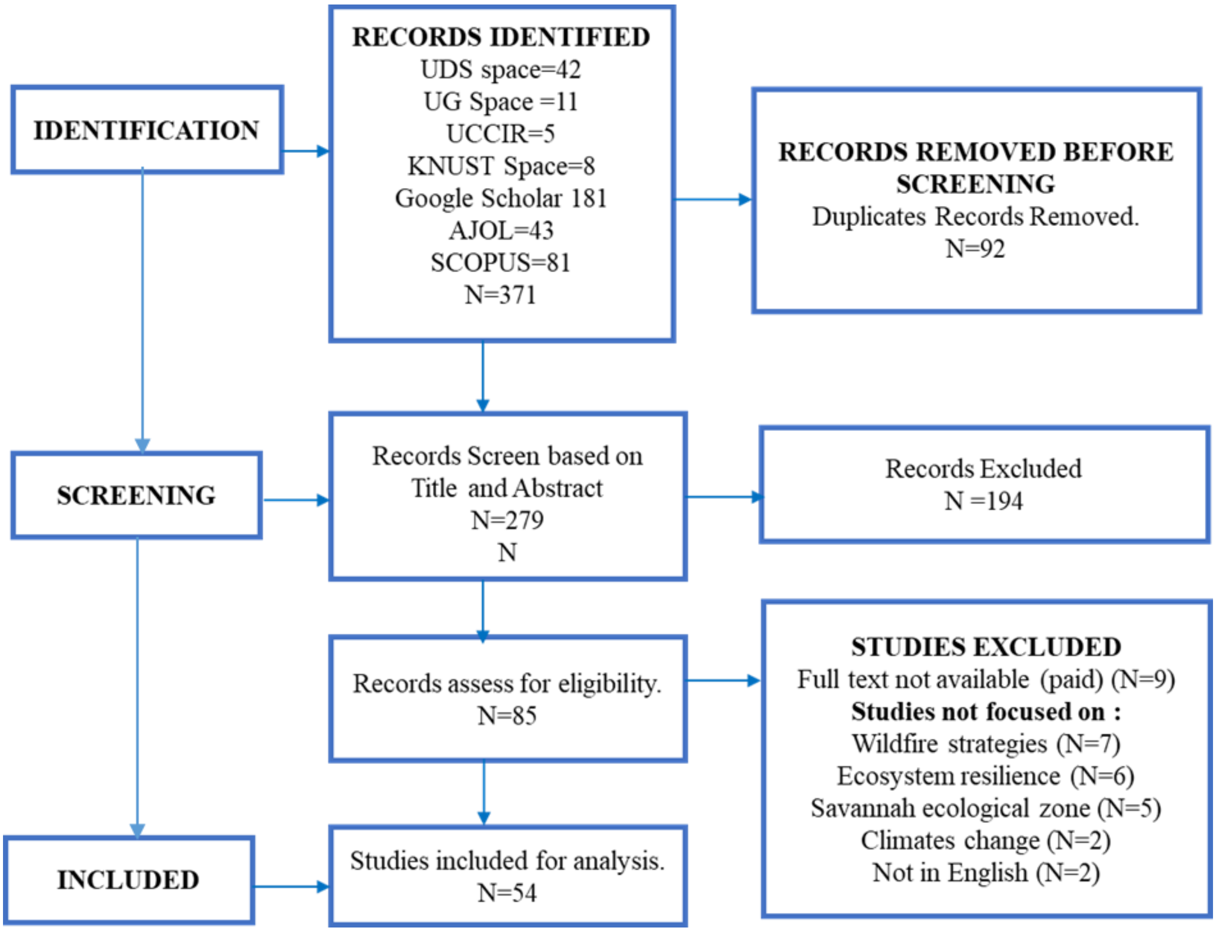

Figure 8: Literature database building, article selection, and categorisation adopted

2.5. Discussions

2.5.1. General Overview of Document Types in Wildfire Management Research

It includes all types of document reviews, from articles and reviews to books and conference proceedings, enriching the breadth of our research. The leading category of documents and articles was crucial in providing specific data for empirical studies in fire regime assessment, and an approach to document types will be essential in articulating strategies for managing wildfires to increase ecosystem resilience in Ghana's savannahs. For example, one study published in Koedoe underlined how fire strategies were adopted and changed across 19 African countries, for which wildfire management had to be done with an approach that was tailor-made in each country's context (Van Wilgen, 2013). Reviews synthesised existing research into comprehensive trends and gaps regarding fire management. These reviews were of the essence in understanding the bigger picture of managing wildfires at both global and regional levels. For instance, a review by Frontiers in Ecology and the Environment contributed insightfully to the role of fire suppression and its long-term implications for biodiversity in fire-prone ecosystems (Van Wilgen, 2013). Books provided in-depth analyses of environmental policy analysis and traditional fire management practices, often setting such practices within historical or socio-political frameworks. Research by Valea and Ballouche, (2012) on the West African savannah was important in underlining the local specifics of fire control and associated socio-environmental drivers.

The proceedings papers captured the ongoing debates, innovations, and policy responses. These were conference and workshop papers, usually giving insight into evolving discussions of climate change adaptation strategies and the role of fire management in mitigating ecological impacts. Each document type contributed cumulatively toward a far more complete understanding of the management of wildfires, from practical applications to theory and policy.

The reviewed documents have been published in several reputable journals. These discussions varied between fire as an ecological process and fire as a management tool from case studies on fire management in protected areas in Koedoe: African Protected Area Conservation and Science Journal. Similarly, some specific articles, such as Sackey and Hale's (2008) study of perennial fires in Mole National Park from the Journal of Science and Technology, were highly relevant to understanding what has occurred in terms of the impact of wildfires on vegetation/ecosystem dynamics. Global Environmental Change highlighted the implications of climate change for the frequency of wildfires in savannahs by relating it to global environmental change. Frontiers in Ecology and the Environment focused on fire ecology and its effects on species composition and habitat structure. However, the Journal of Environment and Earth Science provided various case studies concerning the socioeconomic threats of wildfires, focusing most specifically on Ghana's Upper West Region.

The number of publications in ***Figure 7*** over time underlines several key phases in publication trends: Publication rates from 1985 to 2010 were low, reflecting the little attention management of wildfires in the savannahs of West Africa received at the time. Other pressing environmental issues like deforestation and desertification might be the reason for this. However, from 2011 to 2015, the number of publications visibly rose and peaked in 2015. This may correspond with global efforts against climate change and, specifically, the role of wildfires in exacerbating ecological vulnerabilities. During this period, international organisations took up the cause, linking climate change with the frequency of wildfires, and researchers started seriously studying this aspect, thereby resulting in a spurt in output. A general increasing trend with fluctuations in the number of publications has emerged since 2016. This development might show awareness of wildfires as an integral component of climate adaptation and land management in fire-prone regions. Fluctuations might also be used based on varying research funding levels, changes in the political interest in wildfire management, or periods of severe wildfire events. For instance, the decline in publications for the years 2017 and 2018 could underline a temporary concentration of focus on other environmental subjects, while from 2020 onwards, the interest could be incited by regional collaboration and the strengthened utterance of climate change on fire regimes.

Research trends in publications would depend upon many factors. The increase in publications after 2010 reflects that, after 2010, the impact of climate change on the wildfire regime was recognised internationally, and the Paris Agreement in 2015 has been an impetus for regional studies in climate-related fire management. Another factor that could explain this peak in 2015 is that regional policies in Ghana focused on climate adaptation and fire management. The higher publication rates from more recent years may correspond with the growing recognition of wildfires' ecological and economic impacts on communities in Northern Ghana, where the frequency and intensity of the fires continue to rise. Besides, funding cycles of research, generally characterised by peaks when funds are available through active grants and funding opportunities, also likely played their part in these fluctuations. International funding to address climate change thus provided the impetus toward research activities.

2.5.2. Wildfire Strategies (legislations and policies) implemented in Ghana's Savannah Ecological Zone

The severe drought from 1982 to 1983 caused substantial destruction to forests and land in Ghana, leading to an annual income loss of $24 million and a cumulative GDP decrease of nearly 3%, significantly affecting local people and their ecosystems (Mensah et al., 2015). ***Figure 9*** outlines key milestones in Ghana's fire management strategies, from the Savannah Woodland Policy of 1934 to the Ghana Wildfire Policy of 2006. It highlights legislative interventions such as the PNDCL Law 46 of 1983, which regulated fire use for forestry and agriculture, and the Ghana National Fire Service Act of 1997, which formalised fire response mechanisms. Furthermore, contemporary strategies, including the Ghana National Climate

Change Adaptation Strategy, emphasise integrated approaches to wildfire management in the face of climate change. This crisis prompted the establishment of environmental and forest resource management laws aimed at wildfire management. The Savannah Woodland Policy 1934 was established to promote fire management and discourage burning farmlands and grasslands. However, enforcement mechanisms were weak, and traditional fire-setting practices remained widespread (Boateng, 2016). By 1940, new fire management strategies were introduced, emphasising controlled burning and firebreaks to mitigate large-scale destruction (Owusu, 2005). Despite these efforts, fire outbreaks continued due to a lack of community involvement and insufficient regulatory oversight (Boateng, 2016). Following this, in 1983, the Ghanaian government introduced PNDCL Law 46, which prohibited the initiation of fires for specified purposes such as forestry, game management, or agriculture. Additional legislative efforts, including the formation of the National Bushfire Committee, National Environmental Action Plan, Bushfire Prevention and Control Act, Forestry and Wildlife Policy, the Ghana National Fire Service Act and the Ghana National Climate Change Adaptation Strategy (GNCCAS) were established to address environmental issues and bolster government efforts in bushfire management. Given the increasing frequency and severity of wildfires, the Climate Change Adaptation Strategy sought to integrate fire management into climate resilience frameworks (MESTI, 2013). It advocated for public education on fire hazards, adaptive land-use management, investment in fire research, and early warning systems (UNEP & UNDP, 2019).

Ghana's fire management policies have evolved, demonstrating a progressive shift from reactive to proactive, integrated strategies. Early policies (1930-1940) focused on fire suppression, whereas later frameworks (1980-2000) introduced legal enforcement mechanisms. Recent strategies (2000-2006) emphasise climate adaptation and community involvement. Despite these advancements, challenges such as weak enforcement, inadequate funding, and community resistance persist (Owusu-Ofori et al., 2021).

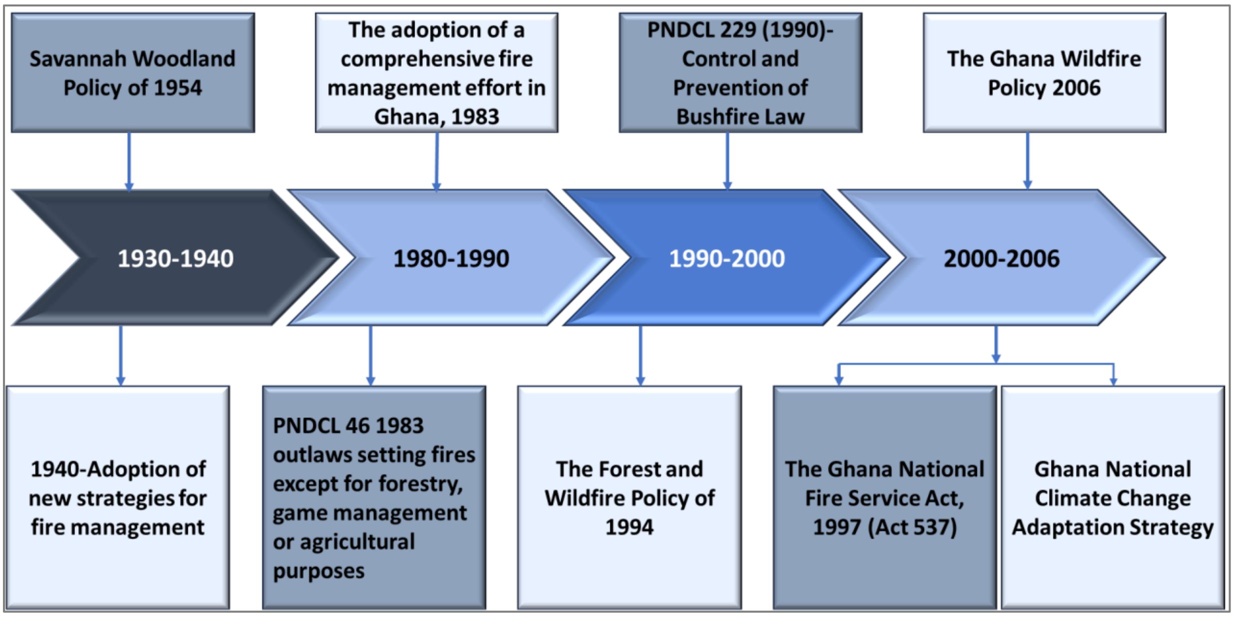

Figure 9: Key Policies and laws that were implemented as efforts to manage wildfires in Ghana from the years 1930s to 2000

The literature review on wildfire management strategies reveals that ***community-based fire management*** has become prevalent in Ghana's Savannah ecological zone (Rosa Diemont & Wanders, 2022). This strategy hinges on the active engagement of local communities and the application of Indigenous knowledge for wildfire prevention, control, and management. It recognises the critical role of communities, including local people and traditional authorities, in ecosystem understanding and management. By encouraging community leadership and ownership in wildfire initiatives, this approach aims to leverage local insights for effective wildfire response (R. Diemont & Wanders, 2023).

Community-based fire management strategies include community education and awareness campaigns to inform residents about wildfire risks, safety practices, management techniques, and early reporting mechanisms (Husseni et al., (2019). Another significant strategy is establishing community fireguards, which involves creating and maintaining clear vegetation-free areas as firebreaks. Additionally, training community-based firefighting crews and monitoring groups has been emphasised, where trained volunteers are equipped to tackle emerging wildfires and conduct traditional surveillance for early detection (Husseni et al., 2019; Diemont et al., 2022).

Incorporating Indigenous ecological knowledge into wildfire management is also recognised as a vital component. This involves integrating local practices and wisdom into contemporary wildfire strategies, facilitating community meetings for strategic planning, and adopting cultural practices to mitigate wildfire risks (Egir & Baidu, 2015). Despite not being fully developed and utilised, some studies propose elements of community-based research and data collection as a strategy by engaging communities and collaborating with local members to collect information on historical wildfires, patterns, vegetation types, causes, ignition sources and other factors influencing wildfires in their communities to understand better the local dynamics of wildfires in the Savannah ecological zone. While Community-based fire management strategies are widely advocated, some highlight the effectiveness of collaborations, legislation, and enforcement as essential to wildfire management in the Savannah ecological zone of Ghana. This includes partnerships among government agencies, district assemblies, local communities, and NGOs and the implementation of programs for vegetation management and sustainable land use to minimise wildfire risks. Enforcing wildfire control legislation and penalising illegal burning activities have been identified as crucial measures (Sackey & Hale, 2008; MLNR, 2006).

Emerging technological tools and research are pivotal in enhancing wildfire management and prevention. Adopting Geographical Information Systems (G.I.S.), remote sensing technologies, and Unmanned Aerial Vehicles (UAVs) for weather forecasting, wildfire prediction, and monitoring has significantly contributed to understanding and managing wildfire dynamics in the Savannah ecological zones of Ghana. These technologies are also employed in monitoring systems and early detection of wildfires through satellite imagery and ground-based surveillance, as well as developing rapid response systems to effectively address and suppress emerging wildfires (Dahan et al., 2023).

2.5.3. Climate Change Impacts on Wildfire Management Strategies and policy regulations to address the challenges of evolving climatic conditions.

Climate change influences wildfires and has significantly impacted wildfire management strategies in the Savannah ecological zone. These strategies face challenges due to evolving climatic conditions. Adapting wildfire management strategies to changing climate conditions requires dynamic and flexible approaches, which are crucial to ensuring ecosystem resilience and efficacy of wildfire management efforts. Climate change significantly affects community-based free management strategies, necessitating frequent campaigns to educate communities about wildfire risks. Local communities must adapt to changing vegetation patterns and prolonged dry seasons, requiring advanced monitoring tools and technology for community-based research and data collection. Furthermore, indigenous knowledge of wildfire practices may need modifications to address climate change impacts on vegetation and fire behaviours. Climate change will impact legislative and policy strategies, necessitating collaboration among stakeholders. Temperature and precipitation changes may interfere with vegetation management programs and sustainable land use practices. These will go a long way in influencing wildfire legislation enforcement, hence requiring some reviews and adjustments.

Climate change could impact the accuracy and reliability of geographic information systems and remote sensing in predicting and managing wildfires. This necessitates continuous refinement of these tools and technology, reevaluation of counterproductive approaches, and collaborative efforts to adjust legal measures to reflect future climate realities.

Wildfires and climate change issues are given significant attention in policy and legislation. Like other countries, policies and legislations related to wildfires and climate change management adaptations in Ghana are often under the broader environmental and forestry framework. Several policies and legislative documents related to wildfire and climate change in the Savannah ecological zone, although no specific policies or legislation exist for this area. The National Forestry and Wildlife Policy (2012) aims to ensure sustainable management, conservation, and utilization of forest and wildlife resources in the Savannah ecological zone. The policy also spelt out a special need for sustainable measures to prevent and manage wildfires, especially in the Mole National Park and reserves and protected areas in the Savannah ecological zone.

The National Climate Change Policy (2013) developed through a consultative meeting between stakeholders integrates climate change considerations into Ghana's development to enhance resilience and reduce vulnerability to climate impacts. The policy emphasizes climate change and proposes strategies to manage wildfires in Ghana's forests, Savannahs, transitions, and ecological zones. The National Disaster Management Organizations Act (2016), the act passed by the parliament of Ghana in 2016, amended and updated the responsibilities of the national disaster management organisations to coordinate and manage disasters and response efforts. The act recognises wildfires, drought, and extreme weather conditions as disasters, and N.A.D.M.O. plays a role in coordinating response efforts, including wildfire management. Other strategies identified are the Ghana national climate change adaptations strategy (2018), the national biodiversity strategy and action plan (2016), and the strategy for reducing emissions from deforestation and forest degradation (REDD+).

2.5.4. The current state of Ecosystem resilience in response to wildfires in Ghana's Savannah ecological zone

Literature classifies wildfires as natural fires and human-induced fires in the Savannah ecological zones of Ghana. Wildfires associated with agriculture and land use activities are termed human-induced fires and wildfires caused as a result of natural occurrences such as lengthening natural fires; some studies reviews consider natural fires as an integral part of Savannah ecosystems and acknowledge their crucial role in maintaining the structure, functions, and effectiveness of ecosystem management and conservations in the Savannah ecological zones on Ghana.

According to Appiah, (2021), ecological adaptation to natural wildfires in Ghana's Savannah ecosystem has evolved, enabling some plant and animal species to develop mechanisms to cope with and adapt to fire incidents in the ecological zone. Certain plant species in the Savannah ecological zone have been identified to develop fire-resistant bark and grow seeds that can germinate despite the impact of fire occurrences. Likewise, some animal species have developed mechanisms and behavioural patterns to respond to and escape fire destruction. The biodiversity balance of the Savannah ecosystem is essential for ecosystem resilience; studies identified natural fires to play a critical role in maintaining the biodiversity of the Savannah ecosystem by thwarting the dominance of single species and promoting diversity in plants and animals by creating a mosaic of different vegetation types and successional stages which is very necessary for the resilience of the ecosystem as a whole and recovery from wildfire disturbances. Additionally, natural fires have been identified to create dynamics in vegetation in Savannah ecosystems. Low-intensity natural fires control vegetation density, reduce wildfire risk, and create suitable conditions for plant species regrowth and reproduction while also preventing woody vegetation encroachment in Savannah ecosystems. Natural fires control tree and shrub expansion in grass-dominated Savannahs, preventing conversion into closed woodlands essential for maintaining Savannah ecological zones and biodiversity (Antwi et al., 2014). The combustion of some vegetation releases some nutrients into the soil, promoting the cycling of nutrients and soil health and the availability of essential elements for plant growth. Some plant species in the Savannah ecosystem require triggers from fire heat or reactions from fires for germination and regeneration to establish and rapid regeneration of the ecosystems. Studies suggest natural fires as a fire management tool with controlled burns adopted by conservations and land managers to prevent fuel buildup and wildfire damage (Appiah, 2021).

Anthropogenic fires negatively impact biodiversity, causing habitat fragmentation, reduced genetic diversity, and vulnerability to environmental changes. Preventing, controlling, and managing these fires presents challenges in ecosystem resilience in the Savannah ecological system. The striking balance between meeting human needs such as agriculture, settlement, and development and preservation of ecological integrity in the Savannah ecological system poses a complex task; mitigating human-induced fires involves fire prevention strategies and controlled burning practices through the various wildfire management strategies to reduce the risk and negative consequences of wildfires. Policies and legislation provide the legal frame which serves as the basis for promoting sustainable practices such as zoning regulations, reservation and management of protected or restricted areas, regulating and banning certain activities during specific periods and places, and the imposition of penalties on illegal burning ensure some level of resilience in the Savannah ecosystem. The adoption and applications of scientific research and technologies to develop evidence-based wildfire management strategies, providing real-time data on fire behaviours, ecosystem health, and development of integrated plans allowing for a holistic approach to wildfire management considering factors like land use planning, conservation goals that balance wildfires with human activities allows for the resiliencies in the Savannah ecosystem.

Wildfire incidents in the Savannah ecological zone often occur in communities, which play a pivotal role in prevention and management. Their intimate knowledge about their environment is essential for effective strategies, and local communities are recognised as active stakeholders in preventing, controlling, and managing wildfires. The community's involvement in wildfire prevention, planning, reporting, and control, as well as utilising indigenous knowledge and community ownership of strategies, is crucial for effective management. Active participation of communities in the creation and establishment of community fireguards, participation in community firefighting volunteer groups, and engagement in education and awareness campaigns allow communities to participate in wildfire management. Using community practices such as taboos, customary laws, and totems in managing vegetation reduces wildfire incidents, and integrating these cultural practices into broader fire management strategies ensures community participation. The contributions of community members to stakeholders' consultative meetings in developing wildfire management strategies, policies, and plans provide an opportunity for local communities' participation. Communities are limited in implementing wildlife policies and enforcing legislative strategies for wildfire management. However, communities actively collaborate with government agencies, district assemblies, and non-governmental organisations for coordinated planning and response actions to ensure multistakeholder approaches in wildfire management strategies.

Also, the applications of scientific research and technologies for evidence-based wildfire management, such as real-time data on fire behaviour, ecosystem health, and integrated planning based on scientific knowledge, contribute to the effectiveness of wildfire management and ecosystem resilience (Mensah et al., 2015). Communities' direct involvement in adopting and using technological tools in wildfire management strategies is limited, even though they benefit from the results of these technologies' applications since they require specialised skills and knowledge. Indigenous knowledge and cultural practices enable context-specific wildfire management, aligning with Savannah ecosystem dynamics.

2.5.5. Effectiveness of Wildfire Management and Prevention Strategies in Ghana's Savannah Ecological Zone.

The utilisation of the wildfire management and prevention strategies identified in the systematic literature review depends on their effectiveness. While some strategies are widely known and used in the Savannah ecological zone, some require technical support and enforcement. Community-based fire management strategies recognise communities' active participation and involve building trust, fostering collaborations, and recognising communities' unique skills and knowledge in preventing, controlling and managing wildfires (Diemont & Wanders, 2023). Education is a crucial step which may increase awareness and lead to responsible behaviour. However, a greater willingness to participate in wildfire management will lead to greater effectiveness. The success of the community fireguards depends on regular maintenance, community commitment, and coordination with more extensive wildfire management efforts. Adapting and integrating Indigenous knowledge can be effective when it aligns with scientific knowledge and contemporary conditions of communities and wildfire dynamics (Paul Laris, 2002). The availability of resources for ongoing training, quick reporting and action, and collaboration with more extensive firefighting efforts and professionals will make the community fire monitoring and community-based firefighting crew effective.

Legislation and enforcement are crucial in managing wildfires; enforcing legislation on land use, wildfires, firebreaks, and illegal burning significantly reduces wildfires incidents. The application of penalties for illegal burning and adherence to wildfire laws and regulations by individuals pose a deterrent to wildfire. The effectiveness of the legislation depends on the clarity and specifications of the legislation related to wildfire prevention and management (Bruce Campbell, 1996). Providing resources and personnel and empowering institutions to enforce the legislation is essential to wildfire law enforcement. Stakeholder collaborations and coordination, such as local government, local communities, and non-governmental organisations, are essential for effective wildfire management. The complexity of wildfire incidents requires a multifaceted approach where different institutions work together.

Technological tools and research as a strategy significantly enhance understanding, early detection, and efficient response in making improved wildfire decisions. Advanced technologies like Geographic Information Systems (GIS), remote sensing, satellite images, and Unmanned Aerial Vehicles (UAVs) aid in the early detection and monitoring of wildfires. Real-time imagery helps identify fire hotspots, track wildfire spread and investigate severity. GIS allows mapping and analysis of wildfire-prone areas, while machine learning and data analytics help identify patterns and trends. Effective wildfire management strategies require integration, collaboration, and public awareness.

2.6. CASE STUDIES

This review synthesised some significant case studies examining the fire dynamics in the savannah ecological zone in Ghana. The research examined fire management strategies, climate change interactions, ecological impacts, and governance frameworks. It recognised intensifying fire incidents, the role of human activity, and gaps in current wildfire control mechanisms in operation. A trend in the research is evident in the use of remote sensing and GIS in monitoring fire and the increase in community-based strategies in controlling and regulating wildfires.

2.6.1. Key Themes and Findings- Policy and Governance

The legal and institutional arrangements for the regulation and governance of wildfires in Ghana are discussed in various research studies. The National Wildfire Policy, presented by M.L.N.R. (2006), aims to reduce fire occurrences through stakeholders' involvement, research, and sustainable natural resource management. Despite this, the implementation continues to be constrained by poor institutional coordination and limited collaboration among agencies (Forestry Commission, Fire Service, local authorities). The Bushfire Act (PNDCL 229, 1990) regulates bushfire control, but research identified poor enforcement and low compliance rates. A Community-Based Resilience Assessment Model, suggested by Antwi et al. (2014), calls for an integrated strategy in incorporating the social, ecological, and engineering elements in the governance of wildfires. Egir, Ofori, and Baidu (2015) and Nantui et al. (2014) further assess how policy gaps impact wildfire adaptation strategies among smallholder farmers. Their findings suggest that financial constraints, lack of information, and weak institutional frameworks hinder the adoption of effective fire management strategies. There is a critical need for cross-sectoral policies that integrate scientific advancements with local governance structures.

2.6.2. Community-Based Fire Management

Community-led wildfire control and management are becoming effective alternatives to centralised approaches. Research by Lignule (2017) and Kosoe et al. (2015) emphasised the importance of local leadership and participatory mechanisms in fire control. The Goziiri community's self-mobilisation efforts in combating the menace of bushfires showcase how transformational leadership and collective effort can suppress the incidence of bushfires. Despite this, challenges such as encroaching fires, a lack of incentives, and low participation rates remain. Acheampong (2013) and Antwi et al. (2014) also provided evidence to support this assertion by illustrating how some members still engage in fire-induced clearing to undertake subsistence farming despite the adverse effects of wildfires. They argue that participatory strategies are vital for reducing fire vulnerability, yet limited local engagement and inconsistent fire regulations hinder effectiveness. This situation calls for education and supportive policies to encourage the community to adopt sustainable fire management practices.

2.6.3. Fire Regimes and Climate Change

Research suggests a profound linkage between climate variability and the intensification of wildfires in Ghana. Dahan et al. (2023) and Nyadzi et al. (2015) show that increased temperature and erratic rainfall have significantly contributed to longer and hotter fire seasons in the Guinea Savannah and Forest-Savannah mosaic zones. Datchoh et al. (2023) identified a seasonal trend where fires peak between November and February during dry seasons and are coupled with human activity, which is the most dominant fire period. Furthermore, Dwomoh & Wimberly (2017) advanced the observation, characterising various fire regimes in West Africa, with the northern Savannah experiencing the highest due to vegetation type, Land use changes and climatic factors. The study accentuates the urgent need for climate-adaptive wildfire management policies integrating scientific data and indigenous knowledge.

2.6.4. Effects of Fire on Vegetation and Soil

Several studies focused on the long-term impact of wildfires on the ecosystem structure and soil properties. Sackey & Hale (2008) describe how perennial fire decreases perennial vegetation density, and the larger the size, the worse the fire scars. The impact of fire on soil composition, indicating that seasonal fires affect soil fertility, and how fire frequency is most dominant in wet and open savannahs are discussed by Amoako and Gambiza (2019). Kusimi and Appati (2012) provided evidence of biodiversity loss and environmental degradation, linking increased fire frequency to weak legislation and inadequate community engagement. These studies all point to frequent fire accelerating ecosystem deterioration and the necessity of developing fire-adaptive land management.

The reviewed research provided a comprehensive image of the dynamism of wildfires in Ghnana's Northern Savannah, showcasing the complex interactions between fire regimes, human activities, and climate change. Community-based strategies are hopeful if further support from the policymaker is needed and incorporation into technological developments is desired. Future research should prioritise long-term fire impact assessments, improved remote sensing accuracy, and cross-sectoral collaboration to enhance wildfire resilience.

2.7. CHALLENGES AND GAPS

This systematic literature review identified some underlying challenges associated with Wildfire management strategies and ecosystem resilience in the Savannah ecological zone.

Technological barriers, especially limited access to geographic information systems (G.I.S.) and remote sensing technologies and data impede the adoption of these technologies in wildfire management strategies. These barriers hinder real-time monitoring, early detection, and data-driven decision-making and planning. Also, there are challenges with policy implementation and regulation enforcement: Consistency in enforcement, non-compliance with wildfire regulations and policies, and ineffective implementation and enforcement pose obstacles to wildfire management strategies, leading to increased fire risk and habitat degradation. Another key challenge concerns changing adaptation conditions since ecosystem dynamics continually change and evolve, requiring strategies to adapt to these changing conditions; failures to adapt these strategies, such as regulations, policies, and technologies, render them less effective over time. Climate change patterns, such as temperatures and precipitation, influence wildfires; therefore, for them to be effective, wildfire strategies require continuous assessment and adjustment to meet the evolving climate conditions.

Existing literature on ecosystem resilience in Ghana's northern savannah ecological zone also revealed some gaps.

- Although several works of literature discuss human-induced and natural fires separately, further studies or research could explore an integrated approach that considers both fires' interactions and cumulative impacts.
- Several studies and research investigations investigated the short-term impacts of wildfires. However, long-term monitoring is needed to understand ecosystem recovery and adaptation of the Savannah ecological zone over time.
- The literature hints at the influences of climate change on wildfires, but expanded research is required to comprehensively understand how the changing climate patterns directly impact the frequency, intensity, and behaviour of wildfires in the Savannah ecological zone of Ghana.
- The literature mentions technological adoption but does not explore barriers to it and its suitability for all areas. Further research is needed to investigate the impediments, applicability to all areas, and potential solutions for the broader adoption of these technologies.
- Policies and regulations have been discussed. However, further studies are needed to assess their impact, the effectiveness and enforcement of wildfire regulations, and the national, local, district, and regional challenges.
- Community resilience and ecosystem recovery mechanisms: Further research is needed to investigate communities' resilience in the aftermath of wildfires, considering psychological, social, and economic aspects to develop strategies that support community well-being. Additionally, the mechanism and process involved in ecosystem recovery from wildfires, such as the role of specific plant and animal species in the regeneration process, must be further explored.

2.8. FUTURE RESEARCH DIRECTIONS AND CONCLUSION

The gaps identified necessitate investigating Climate change impacts and conducting an in-depth assessment of the study area's long-term effectiveness, scalability, and factors contributing to wildfires. These gaps also provide the basis for researching ecosystems that are likely to be directly impacted by wildfires.

While Ghana has wildfire management policies and legislation, their compliance cannot be guaranteed. The review highlights that legislation, such as the National Wildfire Management Policy, Forestry Commission and Environmental Protection Agency legislation, provides a good foundation. However, compliance deficits at both levels, region and locality, predominate. Community fires, planned burning, and land-use planning need more stringent compliance regimes to reduce wildfire incidents and their severity. Institutional coordination, funding, and community incorporation in compliance processes hamper legislation effectiveness. Climate change has heightened wildfire risk by altering rainfall patterns, increasing temperatures, and prolonging droughts, leading to more frequent and intense fires. Ghana's current wildfire management strategies are not fully equipped to handle these evolving climate challenges. While efforts like climate-smart agriculture and afforestation programs are being introduced, they have yet to be effectively integrated into wildfire prevention policies. To build resilience against future climate uncertainties, more research and policy initiatives are needed to align fire management strategies with climate adaptation frameworks.

The savannah ecosystem's fire resilience depends on maintaining biodiversity, ruling out monoculture, and permitting regeneration of fire-adapted species. Savannah's ecological processes rely on fires, but human-induced fires make them fall out of balance, and habitat loss and biodiversity loss ensue. Fire-sensitive species like Vitellaria paradoxa and Daniella oliveri get endangered in frequently burnt lands, but fire-tolerant species like Combretum molle become dominant in such lands. Ecosystem function, carbon sequestration, and productivity suffer long-term in such a situation. Long-term ecosystem monitoring and ecological land use must be given increased attention, with provision for ecosystem recovery after a wildfire.

Existing wildfire prevention programs, particularly community-based programs, have been effective in enhancing fire management but have not yet been optimised in application. Indigenous fire management practices, such as burning at specific periods of the year and traditional firebreaks, have been effective but have not been included in formal policy. Technology, such as GIS, remote sensing, and real-time monitoring, has been effective in early detection and response. However, it is unavailable to most local agencies because of financial and technical constraints. Institutional capacity, public awareness, and integrating scientific technology with traditional knowledge will significantly improve fire prevention and mitigation programs.

This review identifies that wildfire management in Ghana's Savannah ecological zone must go beyond scattered interventions towards a coordinated and adaptive one. Building a firm policy, including the incorporation of climate resilience, community engagement, and increased technological use, will become imperative for wildfire management in a sustainable manner. Long-term trends in fires, ecosystem restoration processes, and socioeconomic consequences of wildfires will have to become a part of future studies to make more balanced frameworks for managing fires.

CHAPTER THREE:

EXAMINING THE DRIVERS OF WILDFIRES AND THEIR IMPACTS ON SAVANNAH ECOSYSTEMS IN NORTHERN GHANA.

Part of it was submitted to Scientific African for publication: *Spatio-Temporal Dynamics, Drivers of Wildfire Occurrence and Distribution in the Northern Savannah Ecological Zone of Ghana.https://www.sciencedirect.com/science/article/pii/S2468227625000511?via%3Dihub*

3. ABSTRACT

This study examines the spatiotemporal and underlying causes of wildfire incidents, using Moderate Resolution Imaging Spectroradiometer (MODIS) data spanning 2000 to 2021 and climate data from NOAA (covering 1992 to 2022) aim to uncover fire trends and how they relate to climatic variables, vegetation types, and human activities. 432,153 active fires were documented during this period, with the largest burned area recorded in 2002 (33,883.4 km²) and the highest fire frequency in 2011 (28,943 fires). Statistical analyses using Ordinary Least Squares (OLS) regression and Geographically Weighted Regression (GWR) models identified proximity to settlements, slope gradient ($p < 0.05$), and maximum temperature ($p < 0.01$) as significant predictors of wildfire occurrence. The analysis evaluated the spatial distribution of wildfires and their key drivers, including land use, settlement proximity, slope, and temperature. The GWR model provided the best fit, explaining 92.3% ($R^2 = 0.923$) of the variance in wildfire occurrence, highlighting maximum temperature, settlement proximity, and slope gradient as the most significant predictors. Findings identified hotspots in West Gonja and Mamprugu Moagduri with higher fire radiative power, typically observed during dry seasons, especially between December and February when temperatures soar. The Mann-Kendall trend test revealed a significant reduction in total burned areas over time ($p = 0.015$). However, there was no noticeable trend concerning the frequency of active fires throughout the studied period ($p = 0.499$). Results suggest that although climatic conditions significantly contribute to wildfire dynamics, anthropogenic actions and topographical features play crucial roles in influencing both occurrence and spread. The study concludes that strategies focusing on climatic vegetation and human aspects are essential for mitigating adverse impacts posed by wildfires within this vulnerable region.

Keywords: Wildfires, Savannah, Ghana, Spatio-temporal, Remote sensing, Fire management

3.2. Background and Problem Statement

Fires are an integral part of land use systems worldwide (Appiah, 2014a). However, in some instances, fires are ignited without valid ecological or land management reasons. Despite this, fires remain a critical tool utilised across various economic, social, and ecological contexts. For example, in slash-and-burn agriculture, fire is used as a land preparation tool (Prasad et al., 2008; Stolle et al., 2003; Fearnside, 2005). Fires are also used for controlling pests, suppressing weeds, promoting the growth of other plant species, enhancing litter decomposition, and returning nutrients to the soil (Archibald et al., 2005). Fires have also been used to prevent the decomposition of palm trees and ensure a better taste and an increased yield of wine during palm wine processing, at least in Ghana (Appiah, 2014). To hunters, fires can serve as smoking out the game (wildlife) (Appiah, 2014b). Thus, fires play a crucial role in land management practices and livelihoods, but they usually become problematic when they get out of control in forests and settlement areas.

In the tropics, including Ghana, uncontrolled fires (wildfires) are increasingly damaging forests, impacting ecosystem processes and shaping the forest landscapes and livelihoods (Kalame, 2009; Hawthorne & W, 1994; FAO, 2001; Cochrane, 2002). According to a recent study (Dahan & Kasei, 2022a), Every year, an average of 684,000 km^2 of land is burned in Ghana, with 372,600 km^2 of the burns occurring in the Savannah zone. Approximately 53%-56% of annual burns in the Savannah zone of Ghana are influenced by wildfires (Kugbe et al., 2012; Dahan & Kasei, 2022b). This could further be exacerbated by climate change and variabilities coupled with an excessive population growth rate in Ghana's Savannah zone in recent years. The cascading effect of wildfires is likely to be high in the vulnerable Savannah zone of Ghana, with severe impacts on the environment, economy, and social fabric of affected areas. Moreover, wildfires affect the succession and service of terrestrial ecosystems by changing vegetation structure and distribution (Chen et al., 2021; Jones et al., 2022), and also feedback on climate change through carbon emissions that disperse and absorb atmospheric radiation (Liu et al., 2018; Sun et al., 2021).

The occurrence and spread of wildfires are conditioned by natural factors linked to climatic conditions (e.g. temperature, precipitation, relative humidity, wind speed), the state of vegetation (e.g. land use/cover type, water content), the topography (e.g. elevation, slope, aspect) and anthropogenic factors (e.g. settlements, population density, distance to roads) (Kouassi et al., 2022). Achieving sustainable fire management in the Savannah zone of Ghana requires understanding the drivers of wildfire occurrence, considering the biotic and abiotic factors underlying wildfire spatial patterns and distribution. A recent study has assessed the contribution of environmental and climatic changes to the spread of wildfires and trends in Ghana (Dahan et al., 2023a) but with a limited geographical scope (only two out of the fifty-five districts in Ghana's Northern Savannah zone were used for the study). The spatial-temporal dynamics and the contribution of climatic, topography, and anthropogenic drivers of wildfires in other parts of the Savannah zone remain elusive.

Therefore, it is imperative to identify a spatially explicit and localised framework that can effectively capture the spatial non-stationarity and local drivers of wildfires in the study area by unravelling the spatial-temporal dynamics and the contribution of climatic, topography and anthropogenic drivers of wildfires in other parts of the Savannah zone of Ghana for effective wildfire management. Identifying the essential drivers of wildfires is important for wildfire management to limit their damage and promote ecosystem health (Jolly et al., 2015). This study employed remote sensing and geographic information system (GIS) techniques, which are currently the most widely used methods for detecting fire occurrence, distribution, and drivers of wildfires (Cheng et al., 2016). Addressing this gap could improve our understanding and prediction of wildfire patterns in the Savannah zone of northern Ghana.

3.2.1. Research Objectives and Questions

The following objectives were set, and several questions were asked to help achieve the main aim of examining the drivers of wildfires and their impacts on ecosystems in the northern Ghana Savannah ecological zone;

1. To assess the influence of human activities and climate change on wildfire frequency and intensity in Northern Ghana.
2. To analyse the spatial correlation between wildfire occurrences and proximity to human settlements, agricultural expansion, and land use patterns.
3. To examine spatial and temporal variations in burned area trends across different land cover types in the northern savannah zone of Ghana.

3.2.2. Hypotheses

This study formulates the following hypotheses to systematically explore the factors influencing wildfire dynamics in Northern Ghana. It examines the roles of human activities, climate change, and their interactions in shaping fire regimes.

Hypothesis 1: Anthropogenic and Climate Drivers of Wildfires

- **H_{01}:** Human activities (agriculture, land clearing) and climate change (rising temperatures, reduced humidity) do not significantly contribute to wildfire frequency and intensity in northern Ghana.
- **H_{11}:** Human activities and climate change significantly contribute to wildfire frequency and intensity in northern Ghana.

Hypothesis 2: Wildfire Occurrence and Land Use Proximity

- **H_{02}:** Wildfire occurrences are not significantly correlated with proximity to human settlements, agricultural expansion, and land use patterns.
- **H_{12}:** Wildfire occurrences are significantly correlated with proximity to human settlements, agricultural expansion, and land use patterns.

Hypothesis 3: Burned Area Trends and Landscape Variation

- **H_{03}:** There is no significant spatial or temporal variation in burned area trends across different land cover types in the northern savannah zone of Ghana.
- **H_{13}:** There is significant spatial and temporal variation in burned area trends across different land cover types in the northern savannah zone of Ghana.

3.3. METHODOLOGY

Wildfires can be influenced by environmental conditions (e.g., fuel, climate, topography) and human activities (e.g., hunting and clearing of farmlands) (Wu et al., 2020). For this reason, this study followed a two-way approach, which involved surveying the direct causes of human activities and using climate/environmental data to investigate the underlying causes.

Figure 10 provided a schematic representation of the methodology described below, with the ensuing paragraphs providing a more detailed description of the entire process.

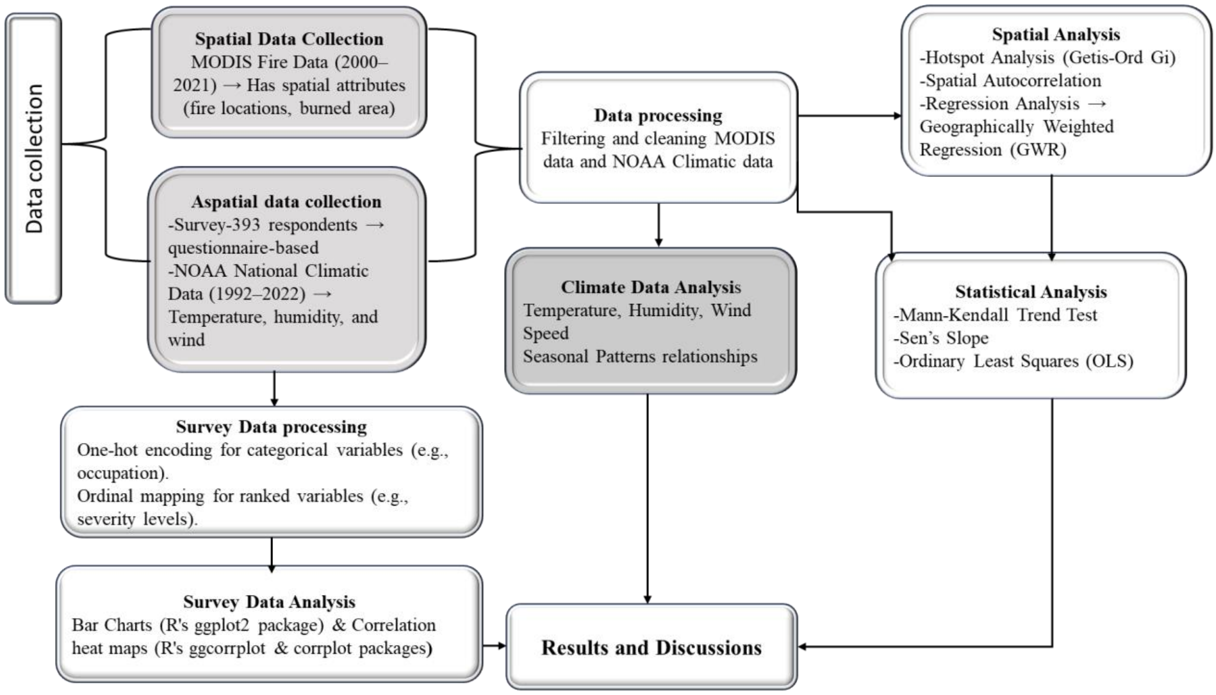

Figure 10: Flow chart of the Data and Methods used for this objective

3.3.1. Data Collection

Sampling Technique (Survey)

Purposive sampling was used to select ten (10) communities for the survey based on MODIS satellite data overlayed in the zone. The study population was stratified based on wildfire risk levels, which were classified into five categories: very high, high, medium, low, and very low. ***Table 3*** below shows how the two communities each were selected from different districts to capture geographical variability (Gbasinkpa, Busunu, Soo, Gushie, Kasaana, Gbal, Siniesu, Gbedembilisi, Bu and Faalu) were selected in each risk-categorised area.

After the stratification, a simple random sampling technique was employed to select the individual respondents. This method was chosen to ensure that the diverse population was well-represented. The sampling process considered gender (ensuring a balance of male and female respondents), occupation (including farmers, traders, students, and other livelihood groups), and dependence on natural resources (particularly in fire-prone areas). The sampling frame consisted of households within the selected communities, from which individuals aged 18 years and above were randomly selected for interviews. At least three adults per household were interviewed to capture intra-household variations in wildfire perception and impact. A household listing was developed in collaboration with local leaders, and each household was assigned a unique identification number. Households were randomly selected using a computergenerated random number approach, and eligible individuals were randomly chosen for interviews within each selected household.

A total of 393 respondents participated in the survey. Gender distribution was relatively balanced, with 216 males (55%) and 177 females (45%). This balance ensures a fair representation of the different wildfire impacts men and women perceive. The selection also considered occupational diversity, with 70% of respondents (over 300 individuals) engaged directly in farming. At the same time, the rest were involved in other occupations, such as students, housewives, and white-collar workers. This focus on farming-based livelihoods highlights the local population's vulnerability to wildfires due to their direct reliance on natural resources. The respondents were selected using the Yamane 1967 formula,

Yamane 1967 formula; $n = N / (1 + N(e^2))$ where: n = sample size, N = total population size

, e = desired margin of error as a decimal (expressed as a proportion of 1). The total population size of the ten communities was (N) =16,387, and the margin of error (e) was 0.05 (5%).

Table 3: Stratification of Study Communities by Wildfire Risk Category and Sample Size Allocation

Risk Categorisation	District	Locality	Projected Population (2022)	Sample Size
Very High Risk	North Gonja	Gbasinkpa	2970	71
Very High Risk	West Gonja	Busunu	3050	73
High Risk	Mamprugu Moagduri	Soo	1604	38
High Risk	Savelugu Nanton	Gushie	1788	43
Medium Risk	Sissala East	Kasaana	968	23
Medium Risk	Sissala West	Gbal	781	19
Low Risk	Builsa North	Siniesu	2346	56
Low Risk	Builsa South	Gbedembilisi	574	14
Very Low Risk	Nandom	Bu	1732	42
Very Low Risk	Lawra	Faalu	574	14

Questionnaire Design

The questionnaire was designed with closed and open-ended questions to capture quantitative and qualitative data. Basic information such as age, gender, and occupation were used to capture the demographic characteristics of the respondents. In addition, Participants were asked about their knowledge of wildfires, the perceived causes of wildfires, and how they believed wildfires affected their communities and livelihoods to ascertain their level of wildfire awareness in their communities. Also, questions were asked to identify the impact of wildfires on resources (e.g., forests, farmlands, water bodies) in the community and ascertain whether ecosystem services, in their opinion, were decreasing or increasing. Pre-testing was conducted in a nearby community to validate the questionnaire's effectiveness. This allowed for feedback that informed minor adjustments to ensure clarity and relevance. Survey questions were designed, and data was collected using https://datatab.net/.

Active Fire Data

The Spatial-Temporal patterns of wildfire occurrence in the Savannah eco-zone of Ghana were assessed using the Collection 6 (C6) wildfire data of the Moderate Resolution Imaging Spectroradiometer (MODIS). Specifically, collection 6 MODIS Global Burned Area Product (MCD64A1) (https://ladsweb.modaps.eosdis.nasa.gov/search/order/), which provides daily global 500m resolution summarised in monthly data, was utilised to map the annual fire occurrence (Annual Burn Area) (Louis Giglio et al., 2018). At the same time, the MCD14DL Collection 6 Global Monthly Fire Location Products (active fires) (https://frms.modaps.eosdis.nasa.gov/download/), which includes geographic coordinates, day of detection, brightness temperature, fire radiation power and detection confidence level with a resolution of 1 km were used to ascertain the spatial auto-correlation of wildfires (Louis Giglio et al., 2013). According to (Giglio & Roy, 2020a), the detection confidence, which ranges between 0% and 100%, determines fire classes (low-confidence fire, nominal-confidence fire, or high-confidence fire) in all fire pixels within the fire mask and helps to trade false alarms, including in the Level 2 and Level 3 fire products (see Table 5). This study employed the use of the nominal and high-confidence fire to rid the inclusion of false alarms (Giglio & Roy, 2020b). This study used data covering 21 years (2000 to 2021) and involved annual fire data downloaded at the peak of the seasonal evolution of wildfire (December) for each year, as opined by (Dahan et al., 2023); Kouassi et al., 2022).

Table 4. Ranges of confidence class assigned to the fire pixels: from (Giglio & Roy, 2020c)

Range	**Confident Class**
0% ≤ C < 30%	Low-confidence fire
30% ≤ C < 80%	Nominal-confidence fire
80% ≤ C ≤ 100%	High-confidence fire

Climate and Environmental Data

In addition to the fire data, this study used various exploratory variables, including climatic data (daily 30-year climate data retrieved from the NOAA National Climatic Data Center online data retrieval tool (https://www.ncdc.noaa.gov/cdo-web/search)); i.e., precipitation, relative humidity, surface soil wetness, maximum temperature, minimum temperature, and wind speed. Vegetation data (i.e., land use, land cover), topographic data (i.e., elevation, slope and aspect) and anthropogenic data (i.e., settlements, distance to roads and distance to watercourses) to determine their influence on burn area and active fires. The 30 years from 1992 to 2022 were selected to observe the gradual change over time in key weather factors like rising temperatures and shifting humidity levels, which are important for figuring out changes in wildfire risks. Looking at data over this time frame allows one to compare findings with those of other studies worldwide, which aligns closely with what the World Meteorological Organization uses for tracking climate shifts. Given the difference in temporal coverage, the analysis integrates multiple perspectives to establish meaningful correlations and identify trends influencing wildfire dynamics. To provide a historical context, long-term temperature and precipitation trends from 1992 to 1999 serve as a pre-fire reference period, offering insight into any significant climate shifts that may have preceded the wildfire satellite records. This baseline assessment helps determine whether changes in climate conditions contributed to the increasing frequency and intensity of fires in the following decades. The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was used to extract the elevation, slope and aspect values of fire pixels to obtain topography data. The elevation data were subdivided into three classes: 0–100 m (low), 100–300 m (moderate) and more than 300 m (high) (Stolle et al., 2003). The slope and aspect values were derived from the elevation data and classified according to the scale used (Garah et al., 2016). This allowed for a comprehensive assessment of the topographic characteristics associated with the fire pixels. The description of these exploratory variables is summarised in ***Table 5*** below. These exploratory variables were selected based on their influence on fire ignition, occurrence and intensity (Munyaradzi Davis Shekede et al., 2021). The Inverse Distance Weighted (IDW) interpolation technique was used to interpolate missing climatic data values in the study area. The distance between them was determined using the Power parameter to control weight decrease on the known data points such as daily maximum and minimum temperatures. A weighted average of the known values calculates the estimated value. The interpolation is repeated for each unknown location, and the Power parameter can be adjusted to create smoother or more localised surfaces. IDW is simple, flexible, and can handle irregularly spaced data points. Moreover, the distance to roads and watercourses was estimated using the Euclidean distance in ArcMap. 10.8. The raw MODIS data was processed to filter out non-wildfire events, ensuring the focus remained on wildfires. Only high-confidence fire events were considered to avoid misclassification and false detections.

Table 5. Description of the exploratory variables used in the study

Data type	Data variables	Acquisition date	Products/Source
Climatic data	Precipitation, relative humidity, surface soil wetness, maximum temperature, minimum temperature, and wind speed.	1991 to 2021	https://www.ncdc.noaa.gov/cdo-web/search
Vegetation data	Land use/cover	1990, 2000, 2010 and 2021	Landsat (30m resolution) and Sentinel (10m resolution) (https://esa-worldcover.org/en) and ESRI land cover
Topographic data	Elevation, slope and aspect	2014	Shuttle Radar Topography Mission (SRTM), Digital Elevation Model (DEM) (https://earthexplorer.usgs.gov/)
Anthropogenic data	Settlements, distance to roads and distance to watercourses.	2020	DIVA-GIS database and open street map (https://diva-gis.org/data.html)

Hypothesis Testing and Statistical Models

The following hypotheses were tested using correlation analysis, regression models, and spatial statistics;

Table 6: Hypotheses Testing and Statistical models for drivers of wildfires

Hypotheses	Statistical Test	Independent Variables	Dependent Variables	Expected Outcome
H_{01}: Human activities and climate change do not significantly contribute to wildfire frequency and intensity in northern Ghana. **H_{11}:** Human activities and climate change significantly contribute to wildfire frequency and intensity in northern Ghana.	-Pearson Correlation Analysis -Multiple Linear Regression (OLS Model) -Geographically Weighted Regression (GWR)	-Human activities (measured via land use and settlement proximity). Temperature, relative humidity, wind speed. Land cover change, climate variables.	Fire frequency (MODIS data	A significant positive correlation indicates human influence on fire frequency. A significant coefficient for temperature/humidity would indicate that climate change influences fire regimes as the expected outcome
H_{02}: Wildfire occurrences are not significantly correlated with proximity to human settlements, agricultural expansion, and land use patterns. **H_{12}:** Wildfire occurrences are significantly correlated with proximity to human settlements, agricultural expansion, and land use patterns.	Spatial Autocorrelation (Global Moran's I & Hotspot Analysis	Fire occurrence points (MODIS), population density, climate variable	Wildfire clustering	Higher fire intensity in areas with both human activities and extreme climate conditions. The clustering of fires near settlements suggests human-driven fires.
H_{03}: There is no significant spatial or temporal variation in burned area trends across different land cover types in the northern savannah zone of Ghana. **H_{13}:** There is significant spatial and temporal variation in burned area trends across different land cover types in the northern savannah zone of Ghana.	Mann-Kendall Trend Test, Sen's Slope Estimator	Burned Area (measured in hectares or square kilometres)	Time (Years: 2000-2021)	Detect a significant trend in the burned area over time

3.3.2. Data Processing and Analysis

Survey Data Processing

Survey data underwent a structured preprocessing phase to ensure accuracy and consistency before analysis. Data cleaning and validation were conducted to identify and correct missing or inconsistent responses, while outlier detection helped maintain data integrity.

Categorical variables were encoded using appropriate techniques to facilitate analysis. One-hot encoding was applied to transform nominal categorical variables, such as occupation, into a format suitable for statistical modelling. This technique involves creating separate binary columns for each unique category within a variable, with **1** indicating the presence of a category and **0** indicating its absence. For example, if the occupation variable included "Farmer," "Housewife," and "Trader," these were converted into three separate columns (Farmer, Housewife, Trader), each containing binary values. One-hot encoding is widely used in machine learning and statistical analysis to handle categorical data because it prevents incorrect assumptions about an ordinal relationship between categories (Pedregosa et al., 2011). It is particularly beneficial when dealing with nominal data, preserving the inherent independence of each variable while minimising potential biases or errors in analysis. By implementing this method, researchers could identify relationships between specific occupations and their perceptions regarding wildfire severity without assuming any ordinal structure among occupational categories.

Ordinal encoding was used to order categorical variables such as wildfire severity and ecosystem resource changes. Numerical values were assigned accordingly, where wildfire severity was categorised as minimal, less severe, severe, and very severe, and numerical values were assigned accordingly. Similarly, Ecosystem Resource Changes were encoded as Decreasing or Increasing. Translating these categories into numbers through ordinal mapping clears the path for seamless correlation analysis with other elements, such as occupation data or various ecosystem changes. The map was created in R using the R's **ggcorrplot** and **corrplot** packages for visualisation.

Survey Data Analysis

Following data processing, a correlation matrix was generated to explore the relationships between key variables, such as occupation, wildfire severity, and ecosystem resource changes. Instead of traditional parametric correlation techniques such as Pearson or Spearman correlation, the focus was on pattern recognition and the visualisation of associations using correlation heatmaps. The correlation matrix was computed in R, leveraging the ggcorrplot and corrplot packages to illustrate the strength and direction of associations between wildfire severity, ecosystem changes, and socio-economic factors. This method enabled an intuitive representation of how wildfire intensity and ecosystem changes relate to different occupations and demographic groups without imposing statistical assumptions about data distributions.

Through this analysis, key insights were derived regarding the relationship between wildfire severity and occupation types, highlighting variations in risk perception across different livelihood groups. Also, the association between ecosystem resource changes (e.g., decreasing vegetation) and wildfire occurrences, identifying potential feedback mechanisms, was derived, as well as the demographic factors, such as occupation and gender, that influence wildfire risk perception.

The correlation heatmap visualisation provided a comprehensive overview of these relationships, offering an evidence-based approach to understanding the interplay between wildfire dynamics and socio-economic factors in the study area.

This structured approach ensures clarity in methodology, explicitly distinguishing how data was prepared and analysed while accurately representing the correlation approach used.

Spatial Data Processing and Statistical Analysis

The MODIS data was filtered to improve data accuracy by selecting only high-confidence fire events. The confidence levels in the MODIS dataset range from 0% to 100%, with less than 30% confidence for low fires, between 30% and 80% for Nominal-confidence fires, and above 80% for high-confidence fires. High-confidence fire events were retained, and the low and nominal confidence was filtered out to reduce the risk of false detections. To organise data geographically and identify spatial patterns in wildfire occurrence, geographic coordinates were grouped, and fire occurrences were aggregated by latitude and longitude. The data were also aggregated temporally by month, summarising the fire occurrences from 2000 to 2021 to capture seasonal patterns in wildfire activity (e.g., more frequent wildfires in the dry season vs. the wet season). The wildfires' Fire Radiative Power (FRP) indicated fire intensity. This value was aggregated across locations to understand the spatial distribution of fire intensities.

The Mann-Kendall test was used to analyse the trend of wildfires over the 21 years. This non-parametric trend test was the outcome of a refinement of the test initially developed by Mann (1945) and then adopted by Kendall (1975). Kendall's t-rank correlation statistic is used to show the degree of significance of the trend and to determine the direction of the trend in the time series. After the Mann-Kendall trend test, Sen's slope was also a non-parametric method used to estimate the trend or slope of the time series data (Jiqin et al., 2023). It is expressed as the change in the response variable per unit change in time. Sen's slope unit depends on the response variable's unit and the time unit used. For example, if the response variable is maximum temperature and the time unit is day, then the unit of Sen's slope would be °C/day. Similarly, if the response variable is rainfall and the time unit is month, then the unit of Sen's slope would be mm/month.

Hot Spot and Autocorrelation of Fire

Fire Radiative Power (FRP) data from satellite observations was used as the input field for the hotspot analysis. FRP provides a measure of fire intensity and energy released. The data was put into a grid or polygon layer for the study area using the Spatial Join tool (Mpakairi et al., 2019). The Getis-Ord Gi statistic was used to determine statistically significant spatial hotspots and coldspots of wildfire activity (Gajovic & Todorovic, 2013). The **Getis-Ord Gi** statistic is an analytical tool for analysing hotspot clusters of high and low values within spatial data. In the context of wildfire analysis, it helps identify significant fire intensity and distribution patterns based on Fire Radiative Power (FRP)(Gajovic & Todorovic, 2013). The data must be spatially referenced to ensure validity, with numeric values representing fire occurrence or intensity. The analysis relies on a defined spatial relationship among observations, typically structured as a grid or polygon layer, where clustering is assessed based on neighbour relationships.

The results of the Getis-Ord Gi analysis were interpreted using Z-scores and p-values. A high positive Z-score indicated statistically significant hotspots where high fire occurrences are spatially clustered, suggesting areas of elevated fire intensity. A low negative Z-score represents coldspots, signifying regions with low fire activity. Z-scores near zero suggest no significant clustering, indicating that fire events are randomly distributed. The statistical significance of these patterns is further assessed through p-values, where smaller values confirm that the clustering observed is unlikely to have occurred by chance(Mpakairi et al., 2019). The Getis-Ord Gi statistic is robust to edge effects and can handle irregular polygon shapes and sizes, making it suitable for analysing fire occurrence data at various spatial scales (Songchitruksa & Zeng, 2010). By leveraging the Getis-Ord Gi statistic, historical fire occurrence data can be analysed to identify significant clusters of high and low fire activity, providing valuable insights for fire management and prevention efforts. This local spatial statistic compares the local sum of a feature and its neighbours to the sum of all features, generating a z-score that indicates the strength of clustering.

Temporal Data Processing and Analysis

The Comma Separated Values (CSV) file was loaded into a data frame containing temperature, relative humidity, and wind speed for each month from January to December. It featured an annual average temperature (ANN) column alongside latitude, longitude, and yearly identifiers. To observe changes over time, data was grouped by the 'YEAR' column to compute yearly averages. This method highlights long-term trends like consistent temperature increases or fluctuations. A line plot was created to visualise these trends easily. Monthly data were also averaged across all locations and years for each month to spot seasonal variations in climate parameters, providing a snapshot of how they shift monthly with peaks or drops evident on another line graph showcasing monthly average temperatures. For comparing wind speeds during dry (December-February) and wet seasons (June-August), months were categorised accordingly. The mean wind speed for these periods was calculated per year and location before grouping the results by year to reveal patterns over time; then, it was pivoted by location for deeper insight into seasonal trends at specific spots.

3.3.3. Data Presentation/Visualisation

Data was presented using bar charts, line graphs and heat Maps to depict the intensity of fire occurrences across different areas. Additionally, line graphs showing the fluctuations in fire radiative power (FRP), temperature, wind speed, and humidity provided a detailed understanding of how climatic conditions influence fire behaviour.

Statistical Models

Ordinary Least Squares (OLS) Linear Regression

Ordinary Least Squares (OLS) regression was utilised to establish the relationship between the dependent variable (wildfire burn area) and several explanatory variables such as distance to settlements, slope, road distance, maximum temperature, and elevation. The explanatory variables used in the OLS regression model were selected based on their ecological significance and expected influence on wildfire dynamics. ***Table*** *7* summarises the variables, their definitions, measurement methods, and units of measurement.

The general mathematical representation of the OLS model is as follows:

$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta 3x3 + ... + \beta nXn + \varepsilon$

where:

- Y represents the dependent variable, specifically the wildfire burn area.
- X1, X2, X3,..., Xn denote the independent variables influencing wildfire occurrences, including distance to roads, distance to settlements, slope, maximum temperature, and elevation.
- β0 is the intercept, representing the expected value of Y when all predictor variables are zero.
- β1, β2,β3,...,βn are the regression coefficients indicating the influence of each predictor variable on wildfire occurrence.
- ϵ represents the error term, which accounts for variability not explained by the model.

The OLS approach aims to minimise the total squared differences between actual observations and predicted values, delivering a unified set of global coefficients applicable across all locations within the study region.

Table 7: Description of Explanatory Variables Used in the Study

Variable	**Definition**	**Measurement Method**	**Unit**	**Data Source**
Distance to roads	Proximity of fire occurrences to the nearest road.	Measured using Euclidean distance analysis in ArcMap 10.8.	Meters (m)	Road Network Data (GIS Database, Ghana Lands Commission)
Distance to settlements	Proximity of fire occurrences to the nearest settlement.	Measured using Euclidean distance analysis in ArcMap 10.8.	Meters (m)	Settlement Data (GIS Database, Ghana Statistical Service)
Slope	Steepness of the terrain at the wildfire location.	Derived from Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM).	Degrees (°)	SRTM DEM Data (NASA/USGS)
Maximum temperature	Highest recorded daily temperature in the study area.	Data obtained from NOAA National Climatic Data Center.	Degrees Celsius (°C)	NOAA Climate Data (National Climatic Data Center)
Elevation	Height above sea level at the wildfire occurrence point.	Extracted from Shuttle Radar Topography Mission (SRTM) DEM.	Meters (m)	SRTM DEM Data (NASA/USGS)

Assumptions of OLS Regression

This model operates under the assumption that relationships between dependent and independent variables remain spatially constant, meaning that the influence exerted by these independent variables is consistent throughout the studied area.

For the OLS model to provide unbiased and reliable estimates, the following assumptions were considered:

- Linearity: The relationship between the dependent variable (wildfire burn area) and the independent variables is assumed to be linear.
- Independence: The residuals (errors) are independent, meaning the data has no autocorrelation.
- Homoscedasticity: The variance of residuals remains constant across all values of the independent variables.
- Normality of Errors: The regression model residuals are assumed to follow a normal distribution.
- No Perfect Multicollinearity: The independent variables should not be highly correlated with each other, ensuring that each variable contributes uniquely to the model.

These assumptions were verified using diagnostic tests such as the Adjusted R^2(used as a measure of model fit; the more significant its value, the better the model fit) to evaluate how much variance in wildfire burn area can be explained by the model; Akaike Information Criterion (AICc)(used for comparing performances of different models; the model with the least value of AICc is always the best) where lower AICc values signify a better-fitting model; and Variance Inflation Factor (VIF) to check for multicollinearity among explanatory variables with a VIF less than 7.5 indicating acceptable levels of multicollinearity. JB is Jarque-Bera's p-value (used to test for normality of residuals in the OLS model).

Geographically Weighted Regression (GWR*)*

Geographically Weighted Regression (GWR) was explicitly applied to address spatial heterogeneity by allowing relationships between dependent and independent variables to differ across various locations within the study area. Unlike OLS, GWR calibrates local models for each observation point, producing spatially varying coefficients that offer richer insights into location-specific drivers of wildfires. By employing a fixed kernel bandwidth and calibrating the model based on AICc values, GWR captures how factors like distance from settlements or maximum temperature affect wildfire burn areas differently across districts. The efficacy of this

GWR model was assessed through Local R^2 values, which indicate its explanatory power at individual locations, also using AICc to compare the GWR model's performance against OLS with lower AICc values to suggest a better model fit. The GWR model proved exceptionally proficient at identifying regions where wildfire drivers differ significantly from overall trends observed in OLS models, thus facilitating an exceptionally nuanced understanding of wildfire behavior across the diverse landscape of the Northern Savannah zone.

3.4. RESULTS

3.4.1. Anthropogenic and Climate Drivers of Wildfires

The analysis of respondents by gender and occupation provided valuable insights into the demographic makeup of the surveyed community. ***Figure 11*** displays that three hundred ninety-three (393) respondents, with 53.9 percent, or 212 individuals, identified as male, while the remaining 46.1 percent, or 181, reported being female. This balanced sample helps ensure that fire management plans consider the varying impacts wildfires can have on men and women. Occupation data in ***Figure 12*** paints an even clearer picture, with nearly half of 177 engaged primarily in farming. An additional 25 percent, or 97, listed their role as farmers and other occupations such as homemakers or students. Smaller subsets included 40 farmer-students, 32 homemakers, 22 students exclusively, 11 combining farming with white-collar work, seven solely white-collar workers, and seven unemployed. Most notable is that over 70 percent of the population, over 300 respondents, depended directly on farming for their livelihood. With such a vast majority reliant on natural resources, especially land and harvests, protecting these vital assets from the threats of wildfires emerges as a top priority. This high dependence on agriculture underscores the community's vulnerability and the need for mitigation tactics to bolster resiliency against wildfire risks.

The survey findings on wildfire awareness shown in *plate 2 Figure 13* are significant, with 363 individuals (92%) acknowledging they know about wildfires and only 30 people (8%) saying they are unaware. This widespread understanding is encouraging, as it suggests the community knows the potential danger of wildfires. However, the 8% unaware represent a segment that may be more susceptible to threats like wildfires. This emphasises the importance of targeted educational initiatives to ensure that everyone in the community is informed and prepared. Examining the figures on the impact of fires on resources on ***plate 2 (figure 14)*** revealed that 254 respondents (64%) mentioned forests and farmlands face the most significant threat; another 117 (29%) mention farm produce and lands, while only 21 (5%) highlight water bodies alongside crops. Only one respondent (0.25%) reported that farm produce, land, and forest are affected. These statistics accentuate that forests and farmlands are the most important resources at risk of being affected by wildfires, which pose economic and environmental challenges. Given that a substantial portion identifies these as crucially affected areas, any strategy to manage wildfires must prioritise safeguarding these critical resources.

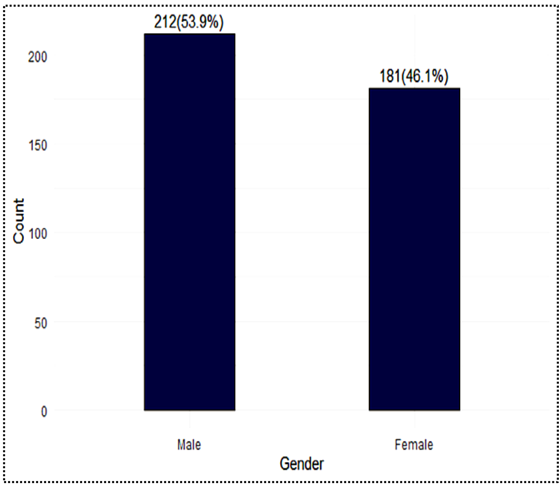

Figure 11: Gender distribution of respondents

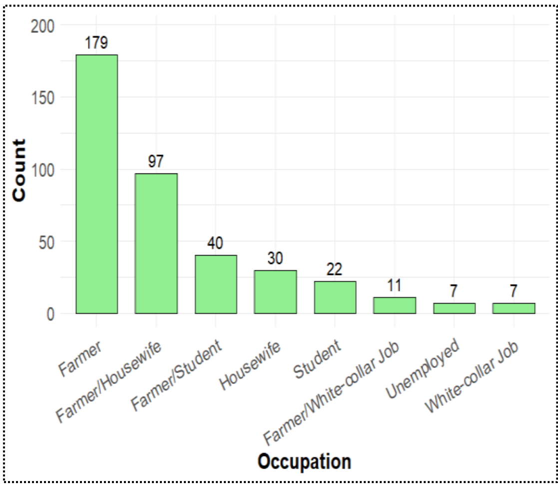

Figure 12: Occupation distribution of respondents

***Plate 1: Gender and Occupation distribution of survey respondents** (Source; Field survey, 2024).*

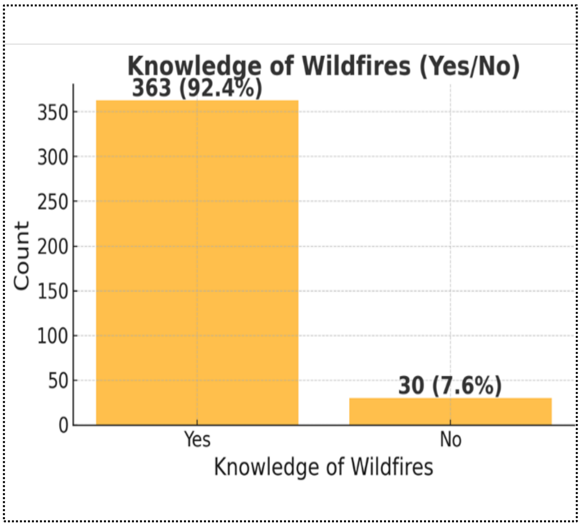

Figure 13: Knowledge of wildfires among respondents

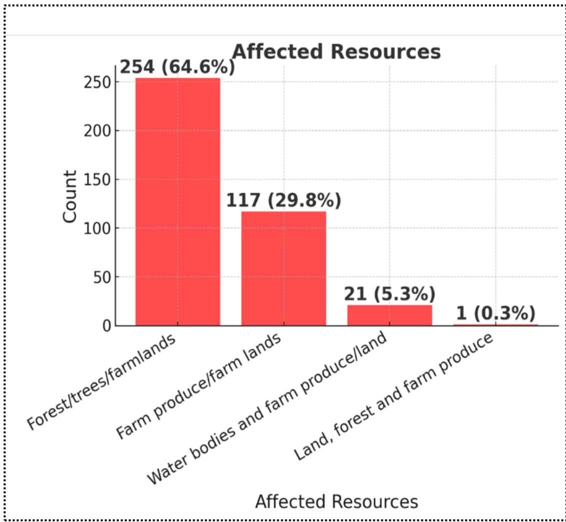

Figure 14 : Resources affected by wildfires

***Plate 2: Knowledge of Wildfires and Resources Affected by wildfires from Survey among respondents** (Source; Field survey, 2024)*

Analysis of Wildfire Dynamics, Climate Factors, and Ecosystem Impacts Using Responses from the Survey

The correlation analysis examined the relationships between wildfire dynamics, climate factors, and ecosystem impacts. Survey responses collected from the communities in the study area sought to understand local perceptions of fire frequency, fire extent, seasonality, and intensity and how these variables relate to changes in climate conditions and ecosystem services. Respondents were asked to rate their experiences and observations on an ordinal scale from 1 (Minimal) to 5 (Severe), allowing for quantitative assessment of perceived trends.

Wildfire Dynamics was assessed based on respondents' fire frequency, extent, seasonality, and intensity observations. Fire frequency referred to how often wildfires occurred in a given year, while fire extent captured the perceived area burned during each wildfire event. Seasonality was evaluated by asking respondents to indicate the peak months of fire occurrences, and intensity was measured based on their perception of fire severity in terms of heat, spread, and difficulty in controlling fires. Climate Factors were measured based on perceived changes in temperature, wind speed, and rainfall over time. Respondents were asked whether they had observed an increase, decrease, or no change in these factors over the past two decades. Temperature perception was rated on a scale of 1 (No Increase) to 5 (Extreme Increase), while wind speed and humidity changes were assessed similarly.

Ecosystem Impacts were evaluated regarding changes in vegetation cover, water bodies, and biodiversity. Respondents rated the extent to which they believed wildfires had contributed to vegetation loss, farmland degradation, reduction in water availability, and loss of economically important tree species such as Vitellaria paradoxa (shea) and Parkia biglobosa (dawadawa).

The heatmap ***Figure 15*** below visualises the correlation between wildfire frequency, temperature increase, humidity decline, wind speed increase, vegetation loss, soil degradation, and water availability decline. Positive correlations (red) indicate strong associations, while negative correlations (blue) represent inverse relationships. The scale ranges from -1 to 1, where 1 signifies a perfect positive correlation and -1 is a perfect negative correlation.

The results indicated a strong positive correlation ($r = 0.76$, $p < 0.01$) between perceived increases in temperature and wildfire frequency, suggesting that respondents strongly associate rising temperatures with more frequent fire outbreaks. Similarly, perceived decreases in humidity were negatively correlated with fire frequency ($r = -0.69$, $p < 0.05$), reinforcing the local observation that drier atmospheric conditions contribute to higher fire occurrences. Wind speed perception showed a moderate positive correlation with fire intensity ($r = 0.58$, $p < 0.05$), indicating that stronger winds are perceived to exacerbate fire spread. In terms of ecosystem impacts, respondents who reported higher wildfire occurrences also indicated greater vegetation loss ($r = -0.72$, $p < 0.01$) and soil degradation ($r = -0.65$, $p < 0.05$), reflecting concerns over declining land productivity. Survey responses also revealed that fire-prone areas exhibited an increase in shrubland cover at the expense of tree cover, with 68% of respondents reporting a decline in forested areas.

Furthermore, 74% of respondents observed a reduced availability of economically important tree species, citing repeated fires as a primary cause of tree mortality. Community perceptions of changes in water bodies also showed significant correlations. Areas with higher reported fire occurrences were associated with perceptions of reduced water availability ($r = -0.62$, $p < 0.05$), with respondents noting that recurring wildfires contribute to increased evaporation, stream drying up, and riparian vegetation destruction.

Survey-based correlation analysis confirms that local communities perceive a strong link between increasing temperature, declining humidity, and the frequency and intensity of wildfires. Ecosystem changes, including vegetation degradation, soil erosion, and loss of economically important tree species, were significantly associated with recurring fire events. Furthermore, communities in areas experiencing frequent fires noted a deterioration in water availability and farmland productivity, highlighting the broader implications of fire regimes on ecosystem services.

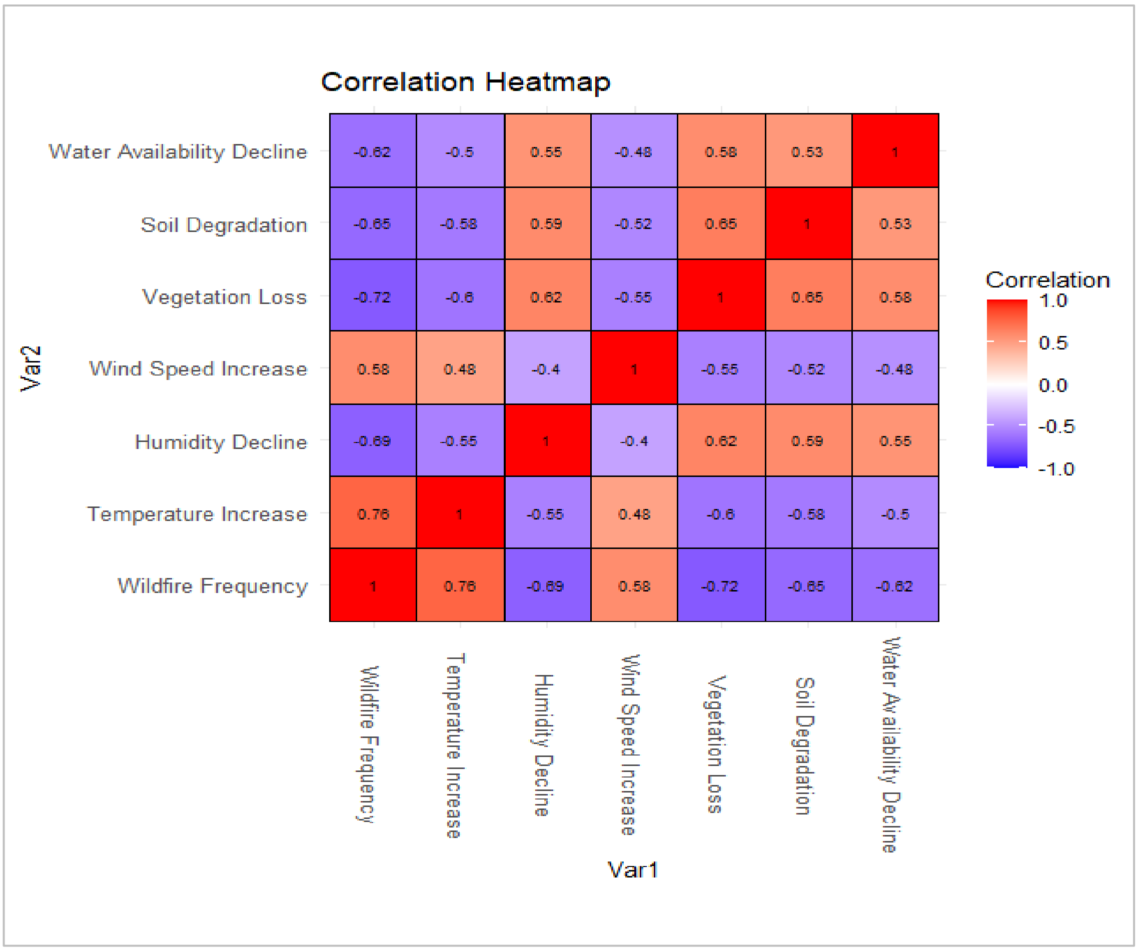

Figure 15: Correlation Heatmap Showing Relationships Between Wildfire Frequency, Climate Variables, and Ecosystem Change in the Northern Savannah of Ghana. *Source: Field survey, 2024*

3.4.2. The Spatiotemporal Dynamics of Wildfires in the Savannah Zone of Northern Ghana

The 21-year dataset (from 2000-2021) revealed a total count of 432,153 active fires, which burned a total landmass of 515,822.7 km2 of vegetation in the Savannah Zone (see ***Table 8***). Annually the highest wildfire occurrence (active fires) was recorded in 2011, with 28,943 fire detections representing 6.7% of active fire counts. The highest burn area happened in 2002, with 33883.4 km2, signifying 34.8% of the Savannah zone. Similarly, the lowest occurrence of active fires was recorded in 2000, with 6501 active fire detections representing 1.5% of the total active fires from 2000 to 2021, while the lowest burn area was observed in 2004, occupying an area of 11,687.5 km2, signifying 12.0% of the entire Savannah zone (see ***Table 8***). It is important to note that the percentages reported in this section do not sum to 100% because they represent different metrics. The burned area percentages indicate the proportion of land burned in a given year relative to the total savannah zone, while the active fire percentages reflect the proportion of detected fires relative to the total recorded fire occurrences (432,153) from 2000 to 2021. Since these two variables are independent, their percentages are not expected to add up to 100%.

Table 8 also displays the yearly distribution of active fires and burned areas. The trends of active fires and burned areas fluctuated throughout the 21 years, showing both increasing and decreasing tendencies. These trends diminished from 2000 to 2021 (**see *Figure 16*).** Peaks in fire activity were observed in 2005, 2010, and 2015, which could correlate with severe weather conditions favouring the spread of wildfires in those years. A notable decline in wildfire occurrences after 2020 may be attributable to shifting climate conditions or improved fire management strategies, as well as the exclusion of lower-confidence MODIS fire data.

Table 8. Burned area and active fires from 2000 to 2021

S/N	Year	Burned Area (km^2)	Savannah Zone Area (%)	Active fires	Active fires (%)
1	2000	28770.1	29.5	6501	1.5
2	2001	21632.9	22.2	6602	1.5
3	2002	33883.4	34.8	25419	5.9
4	2003	32319.0	33.2	21878	5.1
5	2004	11687.5	12.0	17438	4.0
6	2005	27954.6	28.7	21366	4.9
7	2006	23593.1	24.2	24504	5.7
8	2007	27974.5	28.7	21465	5.0
9	2008	24561.9	25.2	20873	4.8
10	2009	19643.8	20.2	21001	4.9
11	2010	19674.1	20.2	18143	4.2
12	2011	28145.0	28.9	28943	6.7
13	2012	25911.7	26.6	19872	4.6
14	2013	23856.5	24.5	19747	4.6
15	2014	28050.7	28.8	23534	5.4
16	2015	19970.6	20.5	26354	6.1
17	2016	22390.6	23.0	15880	3.7
18	2017	20665.4	21.2	19245	4.5
19	2018	18104.1	18.6	22408	5.2
20	2019	20598.4	21.1	17660	4.1
21	2020	16426.3	16.9	16672	3.9
22	2021	20008.5	20.5	16648	3.9
Total		**515822.7**		**432153**	**100**

Both active fires and burn areas exhibited increasing and decreasing trends throughout the 21 years, although each trend (active fire and burn area) generally dwindled from 2000 to 2021 (see ***Figure 16***).

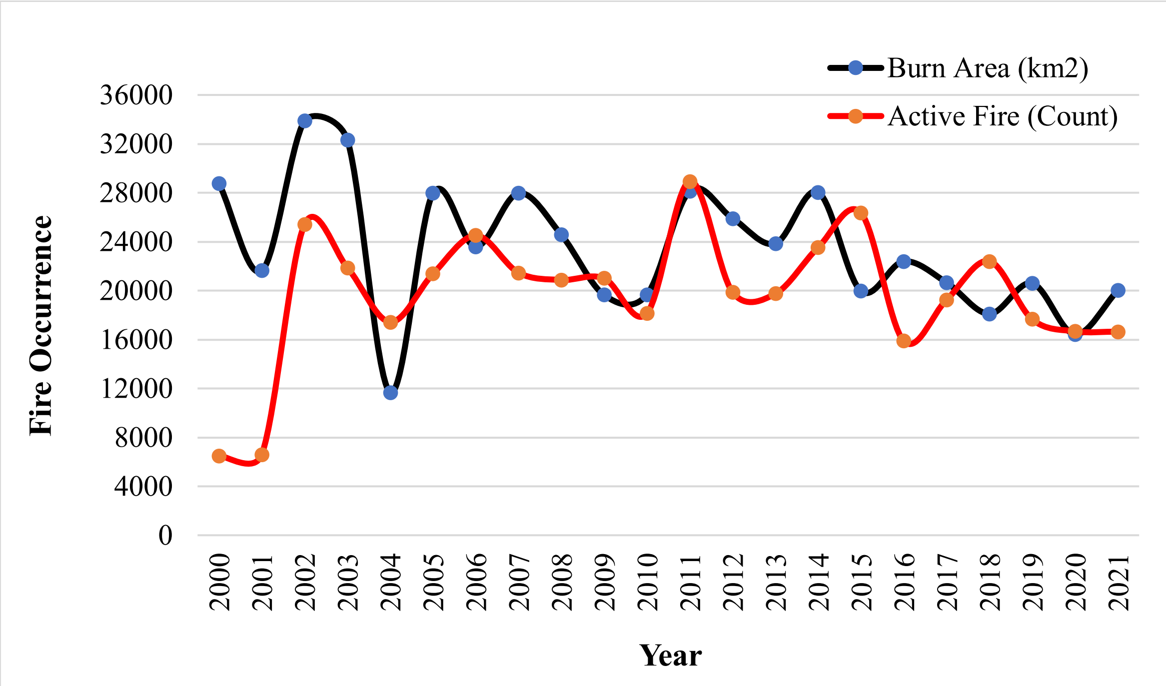

Figure 16: Burned area and active fire occurrence in the Savannah zone; Source: NASA (FIRMS), MODIS Active Fire and Burned Area Products (2000–2021). Retrieved from https://firms.modaps.eosdis.nasa.gov/

Meanwhile, the monthly breakdown in ***Figure 17*** below shows how wildfires follow seasonal changes within the Savannah region per month. Wildfire occurrence is significantly higher during the dry season, with a sharp increase starting in November and peaking in December and January due to drier conditions and increased fire-prone landscapes. The fire count reaches its highest point in December (3000 fires), followed by January (1100 fires) and November (1600 fires). These months are the peak fire season (Nov–Jan), as indicated by the red bars and shaded region.

During the rainy season and transition months (March–September), fire occurrences remain relatively low, with fire counts ranging between 300 and 450 per month, likely due to increased moisture, vegetation growth, and reduced ignition sources. A slight increase is observed from September to October, coinciding with the transition to the dry season.

The 3-month moving average trend (blue dashed line) highlights the seasonal trend, showing a gradual rise in fire occurrences from September, leading to a steep increase from October to December, and a peak in wildfire activity between November and January.

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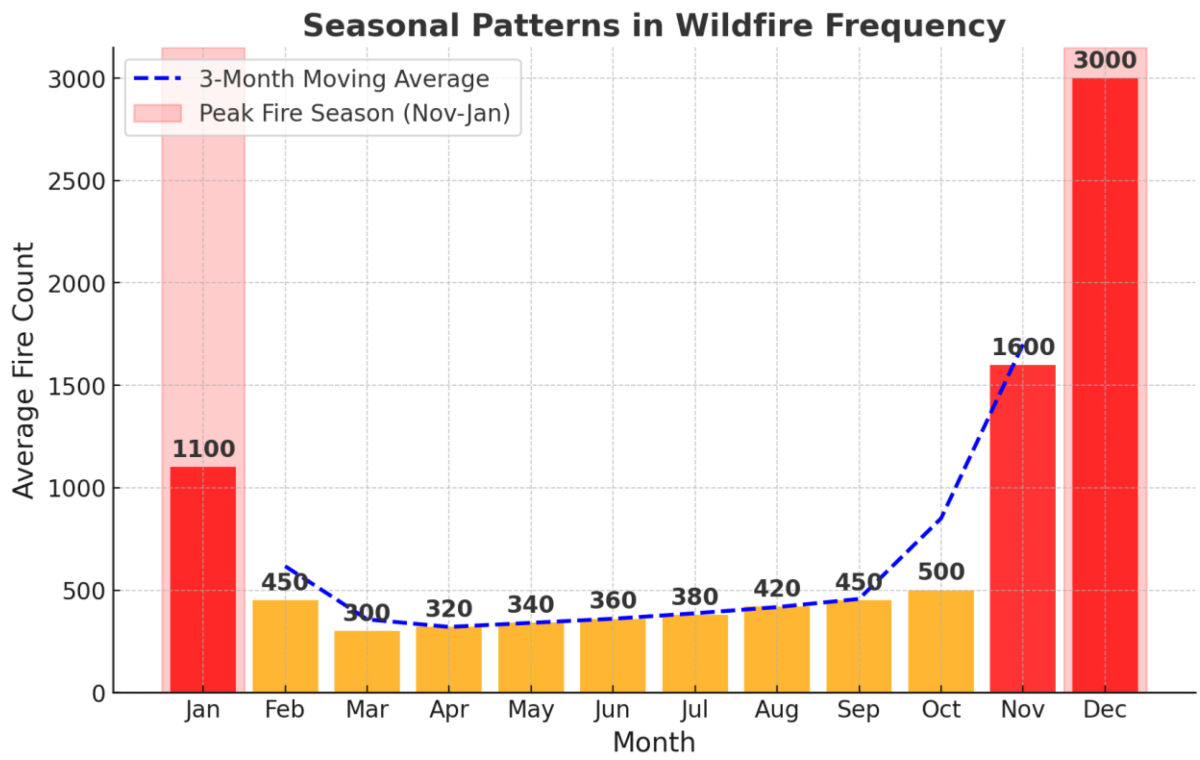

Figure 17: Monthly Seasonal Patterns in Wildfire Frequency from January to December; Source: NASA(FIRMS), MODIS Active Fire and Burned Area Products (2000–2021). Retrieved from https://firms.modaps.eosdis.nasa.gov/

3.4.3. Temperature, Humidity and Windspeed Trends in the Northern Savannah of Ghana

Understanding the shifting trends of important climate factors like temperature, humidity, and wind speed is crucial for figuring out wildfire impacts in the Northern Savannah Ecological Zone. These variables directly affect how often wildfires happen, how intense they are, and how far they spread. This research conducted an in-depth examination to see how these aspects changed over time and through different seasons over 30 years from 1992 to 2022. This analysis examined how warmer temperatures have increased fire dynamics during the dry season, how decreased humidity at certain times enhances vegetation flammability and how wind patterns contribute to the spread and intensity of fires across the region.

Temperature Trends on Fire Dynamics

Figure 18 below represents the yearly average temperature trend, indicating a general increase in temperature over the study period. From the mid-1990s to 2020, the average temperature fluctuated between 38°C and 42°C, with notable peaks in the early 2000s. However, a sharp decline is observed in the final years of the dataset, which may be due to anomalies in data collection or an actual climatic shift. The warming trend aligns with global and regional climate change patterns, potentially exacerbating drought conditions and altering wildfire dynamics in the savanna ecosystem. ***Figure 19***, on the other hand, shows the monthly temperature analysis of seasonal variations. The highest average temperatures occur between February and April, peaking at around 40°C, on the other hand, before declining steadily towards the coldest months of July to September, where the temperature reaches a minimum of around 32°C. This trend corresponds to the dry and wet seasons in Northern Ghana, with the highest temperatures preceding the onset of the rainy season. The temperature increase from October to December suggests a transition from the rainy to the dry season, reinforcing the region's cyclical nature of temperature fluctuations.

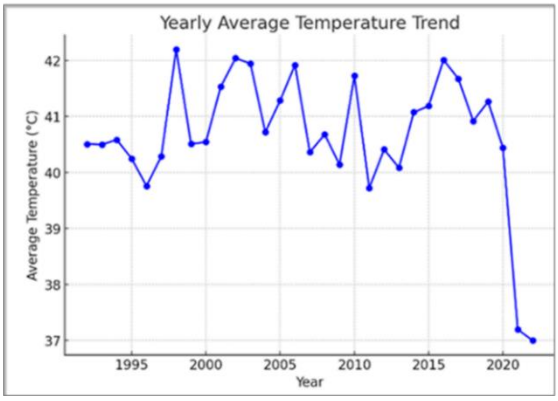

Figure 18: Yearly average temperature

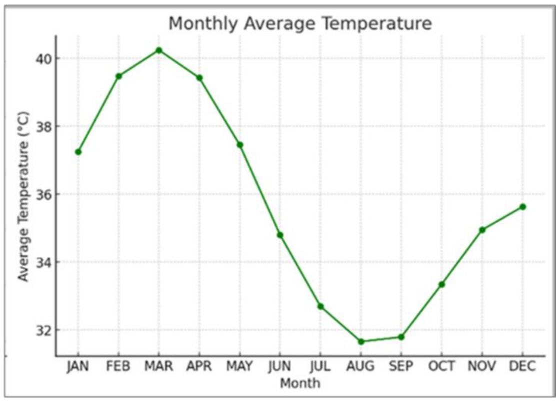

Figure 19: Monthly average temperature

Plate 3: Trends in yearly and monthly Average Temperature observed from the early 1990s to 2020: Source of data: NOAA retrieved from https://www.ncdc.noaa.gov/cdo-web/search

Humidity Trends on Fire Dynamics

The analysis of relative humidity trends in *plate 4* below reveals long-term interannual variability and seasonal fluctuations that influence atmospheric moisture availability. The results indicate fluctuations in average relative humidity over the years, as seen in *(figure 20)*, with a decline around 1999–2001 likely linked to dry climatic conditions or drought events. A steady increase in relative humidity is observed after 2015, peaking in 2020–2022, suggesting possible shifts in atmospheric moisture patterns due to climatic variability. *Figure 21* shows monthly trends with the lowest humidity levels in January and February, aligning with the dry Harmattan season, which increases wildfire susceptibility. Relative humidity rose from March, increasing substantially between July and September during the wet season, before gradually declining towards the dry period in October–December. These observed trends directly affect wildfire dynamics, as the lowest humidity months coincide with increased fire activity.

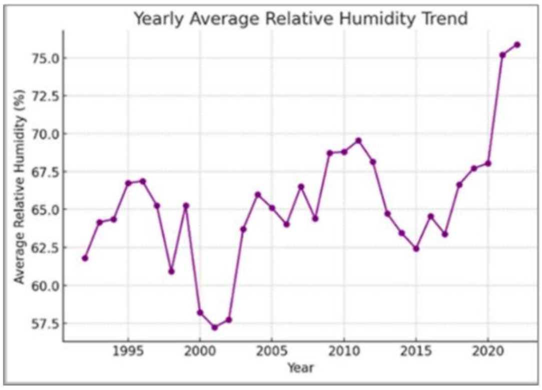

Figure 20: Yearly Average Relative Humidity

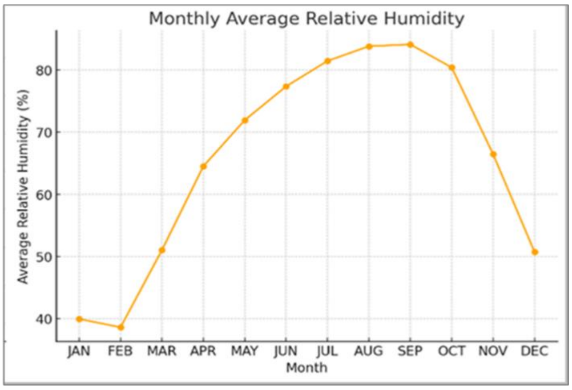

Figure 21: Monthly Average Relative Humidity

Plate 4: Plate 4: Trends in yearly and monthly Average Relative Humidity: Source of data: NOAA retrieved from (https://www.ncdc.noaa.gov/cdo-web/search

Wind speed Influence on wildfire dynamics

Plate 5 provides an overview of the wind speed trends over the study period. The yearly trend demonstrates notable variability in wind speed, with peaks in the early 2000s and a decline around 2010. The first graph, *plate 5 (Figure 22,* shows fluctuations in annual wind speed over the years. The trend is highly variable, with periods of increase and decline. Peaks around the early 2000s indicate higher wind speeds, followed by significant dips around 2010. A slight recovery occurs in later years, but the overall trend suggests interannual variability with no apparent long-term increase or decrease. These fluctuations in wind speed may correspond to periods of increased or decreased wildfire activity, as higher wind speeds promote faster fire spread. The second graph, *plate 5 (Figure 23),* presents wind speed variations across months of the year. Wind speed is highest in January, February, and March, with values above 2.4 m/s. A decline begins in April and continues through September, reaching the lowest point in October and November. There is a recovery in December when wind speed starts increasing again. The pattern suggests seasonal variations, likely influenced by climatic conditions such as the Harmattan winds and monsoonal transitions.

Yearly wind speed variability may be influenced by broader climate variability, including global wind patterns, El Niño-Southern Oscillation (ENSO) effects, or regional land-use changes. The seasonal trend aligns with dry season conditions in regions like Northern Ghana, where the Harmattan wind intensifies in the early months of the year. If wind energy potential is considered, wind turbine efficiency would be higher during the peak months and may require complementary energy sources during lower wind periods.

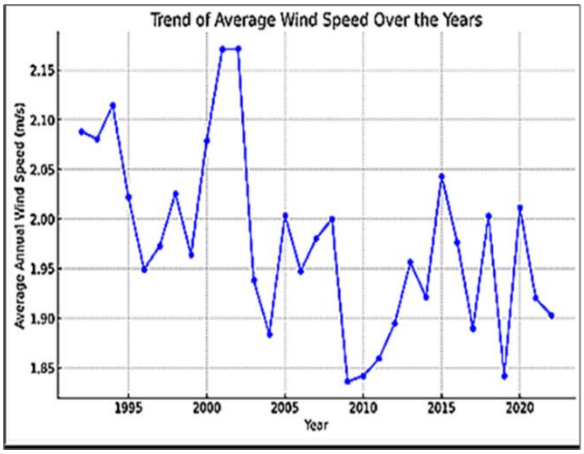

Figure 22: Average Yearly Wind Speed Trend

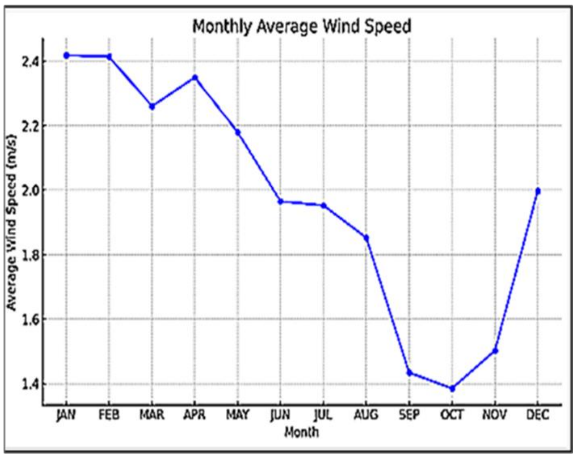

Figure 23: Average Monthly wind speed Trend

Plate 5: Trends in Yearly and monthly Average Wind Speed illustrating fluctuations over time and highlighting seasonal changes. Source of data: NOAA retrieved from; (https://www.ncdc.noaa.gov/cdo-web/search

Comparison of Average Wind Speeds Between Dry and Wet Seasons

Average wind speeds between the dry and wet seasons were compared to assess how seasonal variations contribute to fire behaviour, as seen in *Figure 24*. The analysis reveals that the dry season (Red line) represents the average wind speed during the dry season (typically December-February), the period most prone to wildfires. It exhibits higher wind speeds, with peaks exceeding 2.5 m/s, particularly in the early 2000s and mid-2010s. Alternatively, the wet season (Blue line) shows the average wind speed during the wet season (June-August) and experiences lower wind speeds, averaging around 1.8 to 2.0 m/s, which, combined with higher moisture levels, reduces the risk of fire spread. This comparison underscores the urgent need for targeted fire management efforts during the dry season when wildfire risks are most significant, highlighting the importance of proactive measures.

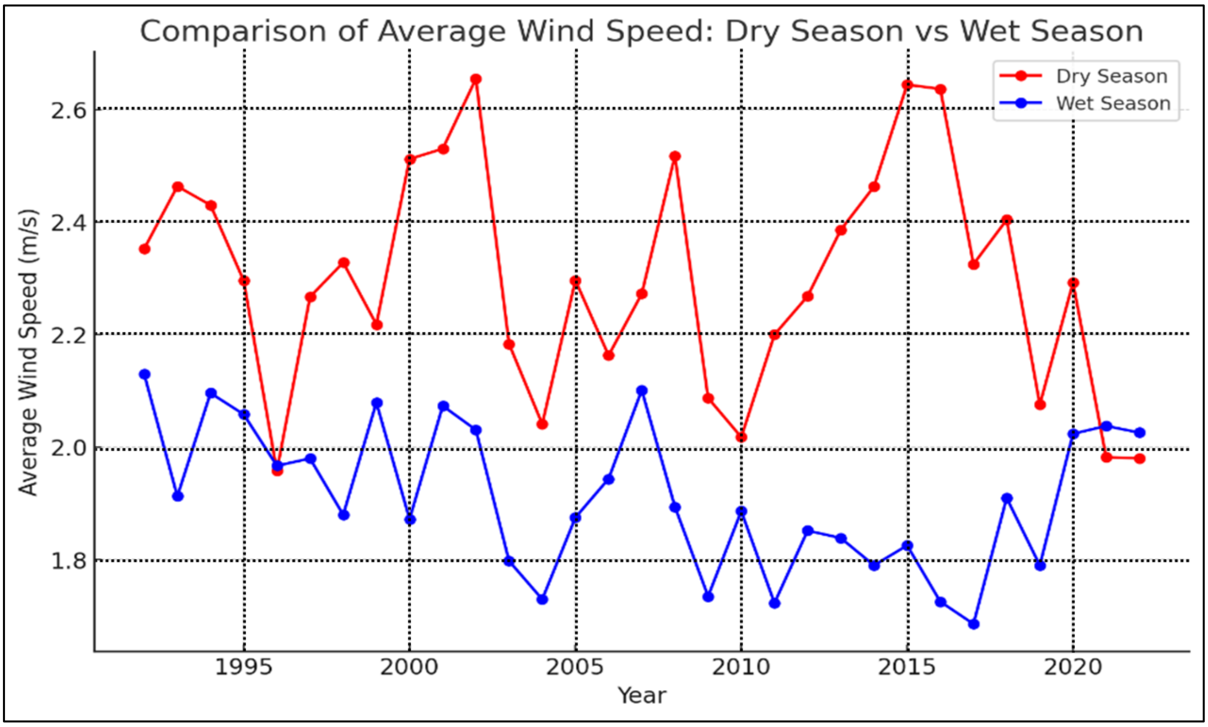

Figure 24: Comparison of average wind speed during the dry season (December-February) and wet season (June-August). Source of data; NOAA retrieved from; (https://www.ncdc.noaa.gov/cdo-web/search

3.4.4. Fire Radiative Power (FRP) in Dry and Wet Seasons (2000-2021)

The temporal variation in Fire Radiative Power (FRP) between the dry season (red line) and wet season (blue line) from 2000 to 2021 is presented in *Figure 25*. The results indicate substantial seasonal differences in fire activity, with higher FRP values in the dry season compared to the wet season, with peaks exceeding 90 MW, particularly in the early 2000s. This pattern reflects the influence of low moisture content, increased fuel availability, and high temperatures during dry periods, which create favourable conditions for intense wildfires. While the dry and wet season FRP exhibit fluctuations, the wet season experiences more abrupt variations, particularly between 2000 and 2005. The decline in FRP after 2005 could suggest possible fire management interventions, land-use changes, or shifts in climatic conditions affecting fire frequency and intensity. However, from 2010 onwards, FRP values for both seasons appear to converge, with reduced fire intensity in the dry season and a more stable wet season trend. This could be attributed to increased fire suppression efforts, agricultural expansion, or changes in vegetation structure affecting fire fuel loads.

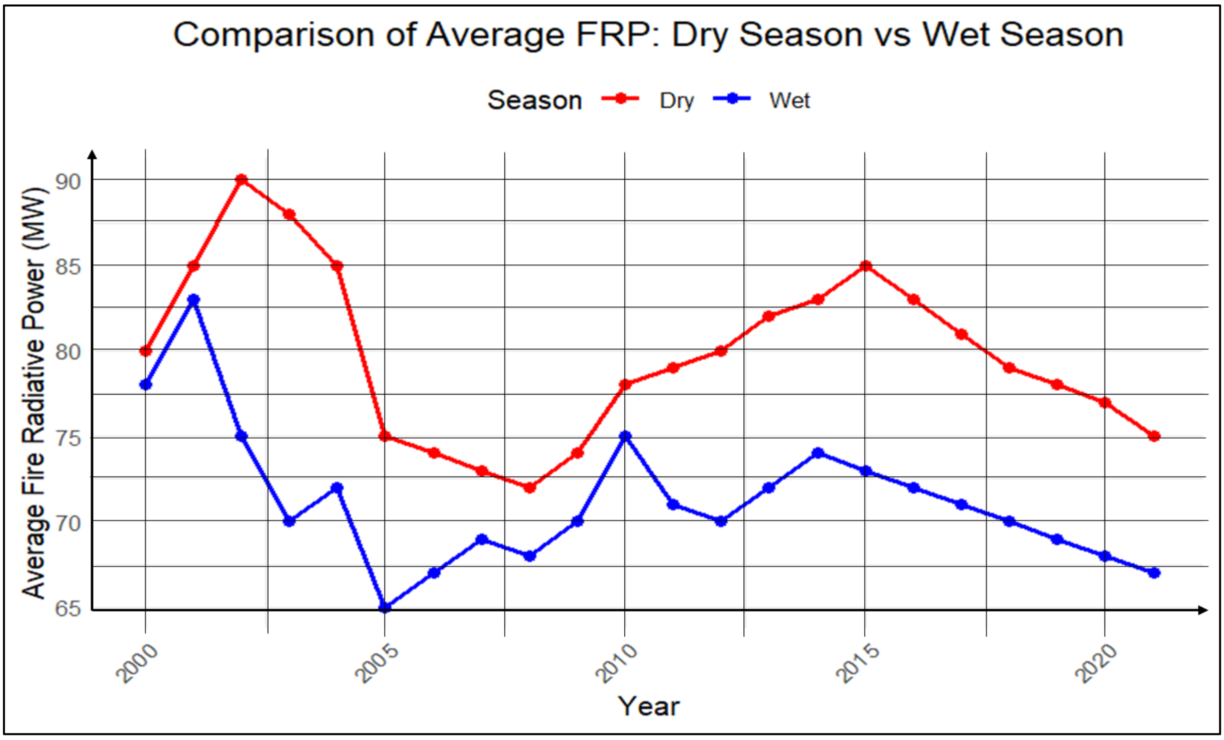

Figure 25: Trends in Fire Radiative Power (FRP) During Dry and Wet Seasons (2000-2021); Source: NASA (FIRMS), MODIS Active Fire and Burned Area Products (2000–2021). Retrieved from https://firms.modaps.eosdis.nasa.gov/

Relationship between Fire Radiative Power (FRP) and Relative Humidity, Temperature

The relationship between FRP and monthly relative humidity is inverse, as seen in *plate 6 (Figure 26)*. FRP is relatively high in the early part of the year when relative humidity is low. As the year progresses, an increase in relative humidity from March to August coincides with a gradual decline in FRP. The peak of relative humidity around August to September corresponds with the lowest FRP values, indicating that high moisture content suppresses fire intensity. However, FRP rises again towards the end of the year, correlating with the decrease in humidity levels from October to December. This seasonal variation suggests that fire occurrences are primarily driven by atmospheric moisture conditions, with higher fire activity during drier months.

On the other hand, the relationship between FRP and monthly temperature follows a more direct correlation, with higher temperatures generally aligning with increased fire radiative power, as shown in *plate 6 (Figure 27)*. The highest temperatures occur from February to April, which coincides with elevated FRP levels, signifying enhanced fire activity due to increased heat and dry conditions. A significant decline in temperature from June to August corresponds with a reduction in FRP, highlighting the cooling and wetting effects of the rainy season. Interestingly, the lowest FRP values in July and August coincide with the lowest temperatures, reinforcing the influence of seasonal climate variations on fire regimes. The subsequent rise in FRP from September to December aligns with increasing temperatures, demonstrating that higher temperatures contribute to increased fire activity, particularly in the dry season.

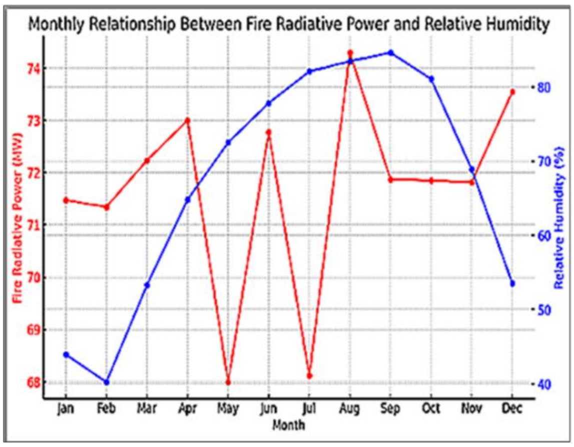

Figure 26: Monthly relationship between FRP and RH

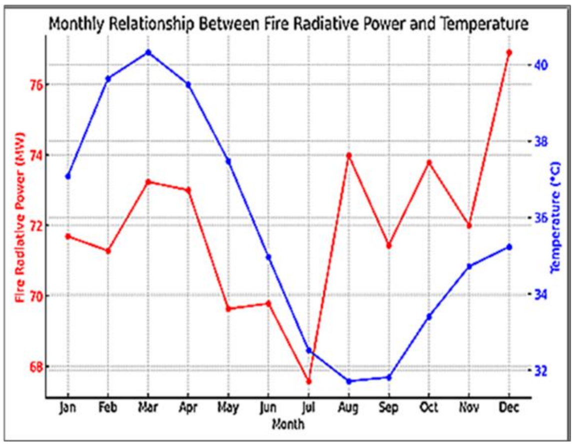

Figure 27: Monthly relationship between FRP and Temperature

Plate 6: Monthly Relationship Between Fire Radiative Power, Relative Humidity, and Temperature. Source: NASA (FIRMS), MODIS Active Fire and Burned Area Products (2000–2021). Retrieved from https://firms.modaps.eosdis.nasa.gov/

Relationship Between Fire Radiative Power FRP and Monthly Wind Speed

The analysis of monthly variations in fire radiative power (FRP) and wind speed reveals distinct seasonal patterns, as seen in (*Figure 28)* below. FRP fluctuates from January to July, peaking in July (74 MegaWatts) before experiencing a gradual decline from August to October, reaching its lowest in September (50 MegaWatts). A slight recovery in FRP is observed from October to December. Wind speed follows a consistent decline from January to September (~1.50 m/s), reaching a minimum in September but increasing from October onward, with a high increase in November and December (~1.75–2.00 m/s). An inverse relationship is observed between wind speed and FRP. Wind speed declines From January to September, and FRP initially fluctuates but decreases significantly later (July–September). Also, from October to December, wind speed increases, and FRP shows a slight recovery. The seasonal variations suggest higher wind speeds can enhance fire spread, but fire intensity may be moderated by fuel moisture content, particularly during wetter months. The decline in FRP from August to October aligns with a likely wetter season, supporting vegetation recovery, while the increase in FRP from October to December may correspond to drier conditions that enhance fire activity.

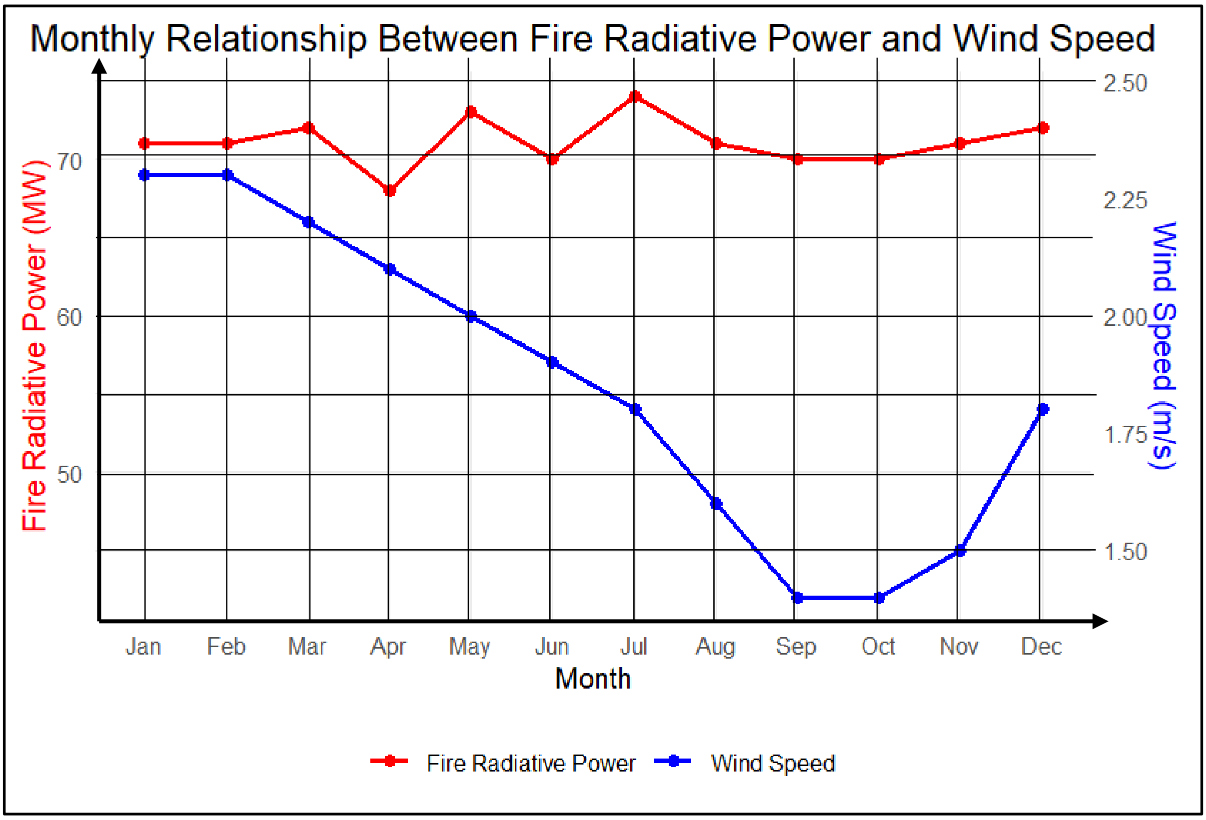

Figure 28: Relationship between Fire Radiative Power (FRP) and monthly wind speed; Source: NASA (FIRMS), MODIS Active Fire and Burned Area Products (2000–2021). Retrieved from https://firms.modaps.eosdis.nasa.gov/

3.4.5. Statistical Trend Analysis of Wildfire

Burn and Active Fire Analysis

This analysis of wildfire trends in the Northern Savannah zone of Ghana focused on burned area (km^2) and active fire occurrence from 2000 to 2021. The Mann-Kendall trend test and Sen's slope estimate were used to detect trends in wildfire occurrences and burned areas over time. The burned area fluctuated over the study period, reaching a peak of 33,883.4 km^2 in 2002, covering 34.8% of the savannah zone, while the lowest recorded extent was 11,687.5 km^2 in 2004, representing 12.0% of the total area (see Table 8 above). A general downward trend was observed, indicating a progressive reduction in burned area over time.

The Mann-Kendall trend test for the **burn area** shows a significant decreasing trend over time with a p-value of 0.015 ($\alpha = 0.05$) and an S-estimate of -87. Moreover, Sen's slope estimate was

-488.633, implying a decreasing trend in the burnt area over time with a p-value of 0.015 at a 95% (-797.2, -118.7) confidence interval (see **Table 9**). Hence, we reject the null hypothesis, which states that "there is no trend in the fire burn area and active fire series". The Mann-Kendall trend test for the active fire shows a p-value (0.499) greater than the significance level ($\alpha = 0.05$). The number of **active fires** varied considerably across the years, with the highest recorded in 2011 at 28,943 fires, accounting for 6.7% of total fire occurrences, and the lowest in 2000 at 6,501 fires, representing 1.5%. Despite fluctuations, the overall trend in active fire occurrences was weakly negative and statistically insignificant. The Mann-Kendall trend test produced a p-value of 0.499 and an S-estimate of -25, indicating no significant or weak downward trend. Sen's slope estimate suggested a decrease of 146.167 fires per year (see Table 9 below); however, the confidence interval ranged from -334.1 to 373.0, reinforcing the insignificance of the observed decline. These findings suggest that while the extent of burned areas has significantly decreased over time, the frequency of active fires has not shown a statistically significant trend. This distinction may reflect variations in fire intensity, ignition sources, and landscape changes rather than a straightforward decline in fire occurrences.

Table 9: Mann-Kendall Trend and Sens's Slope Analysis for Burn Area and Active Fire in Northern Ghana

Variable	Test	Estimate	Z-Value	P-Value	CI
Burn Area	Mann-Kendall	S: -87.000	-2.425	0.015	
		varS: 1257.667			
		tau: -0.377			
Active Fire	Mann-Kendall	S: -25.000	-0.677	0.499	
		varS: 1257.667			
		tau: -0.108			
Burn Area	Sens's Slope	Slope: -488.633	-2.425	0.015	-797.2, -118.7
Active Fire	Sens's Slope	Slope: -146.167	-0.677	0.499	-334.1, 373.0

Hotspot and Spatial Auto Correlation of Active Fires

A spatial autocorrelation analysis was conducted using z-scores and p-values to assess the spatial distribution of Fire Radiative Power (FRP) and to determine whether it exhibited significant ***clustering***, ***dispersion***, or ***randomness. Figure 29*** below presents the spatial analysis results, showcasing a bell curve representing the range of potential z-scores. Values closer to zero indicate random patterns, while values at the extremes (negative and positive) suggest significant patterns of dispersion or clustering, respectively. Z-scores above +1.96 (highlighted in red) suggest a clustered spatial pattern, where events or features tend to concentrate in certain areas. Z-scores below -1.96 highlighted in blue) suggest a dispersed spatial pattern, where events or features are more spread across the study area. Z-scores between -1.65 and +1.65 (yellow) indicate a random distribution with no clear pattern. The ***square box A in Figure 29*** illustrated dispersed or widely spread features, suggesting no concentrated hotspots. The ***square box B*** showcased the random distribution of events, any structure, or relationships. The ***square box C*** represents a clustered/ tightly grouped feature indicating areas where activity is concentrated. The computed z-score of 131.2 and a corresponding p-value < 0.01 indicate less than a 1% likelihood that this clustering occurred due to random chance. This means the observed clustering might have emerged by pure chance without any underlying spatial structure or influencing factors. In statistical analysis, this is tested using a null hypothesis, which assumes that the spatial pattern observed (e.g., clustering of Fire Radiative Power (FRP) values) results from a random distribution rather than an underlying systematic factor like vegetation-type fire regimes or human activities. This suggests that fire occurrences are spatially dependent, with distinct hot spots of high FRP values persisting over time. The clustering is likely influenced by environmental factors, land use patterns, and fire regimes rather than stochastic processes.

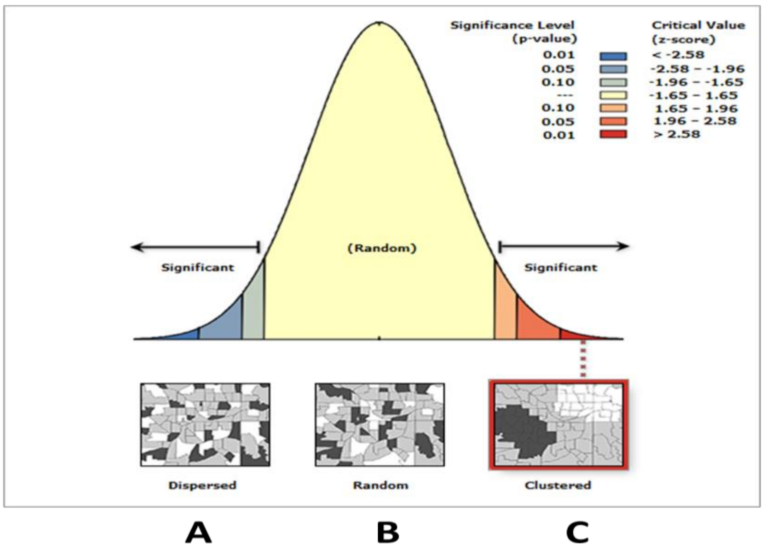

Table 10: Global Moran's I

Moran's Index:	0.06
Expected Index:	-0.000003
Variance:	0.00
z-score:	131.2
p-value:	0.01

Figure 29: Spatial autocorrelation of FRP; Source; Self-generated using ArcGIS Pro Hotspot Analysis and Moran's I

The spatial distribution of FRP over the study period exhibits a highly significant clustered pattern, as revealed by the Getis-Ord Gi hot spot analysis ***(Figure 30).*** Results of hotspot analysis performed on the Fire radiative power (FRP) across the Savannah zone of Ghana over 21 years (2000-2021) revealed the existence of several clustered wildfire hotspots. The wildfire hotspots were spatially occurring at the north-central and the west-central of the Savannah zone, mainly in the Upper West, Savannah, and North East Regions of the Savannah zone, with smaller patches observed in the Northern Region. The districts with high concentrations of wildfire hotspots include West Gonja, North Gonja, Mamprugu Moagduri, Sissala East, and Saboba. Some isolated fire hot spots were observed in the Chereponi, Wa East, Sissala West, Sawla-Tuna-Kalba, Kumbungu, West Mamprusi, Bole, Central Gonja, Karaga, and North/East Gonja districts. Contrarily, wildfire cold spots were predominantly observed in all the districts in the Upper East region of Ghana, with non-significant clusters scattered across the landscape.

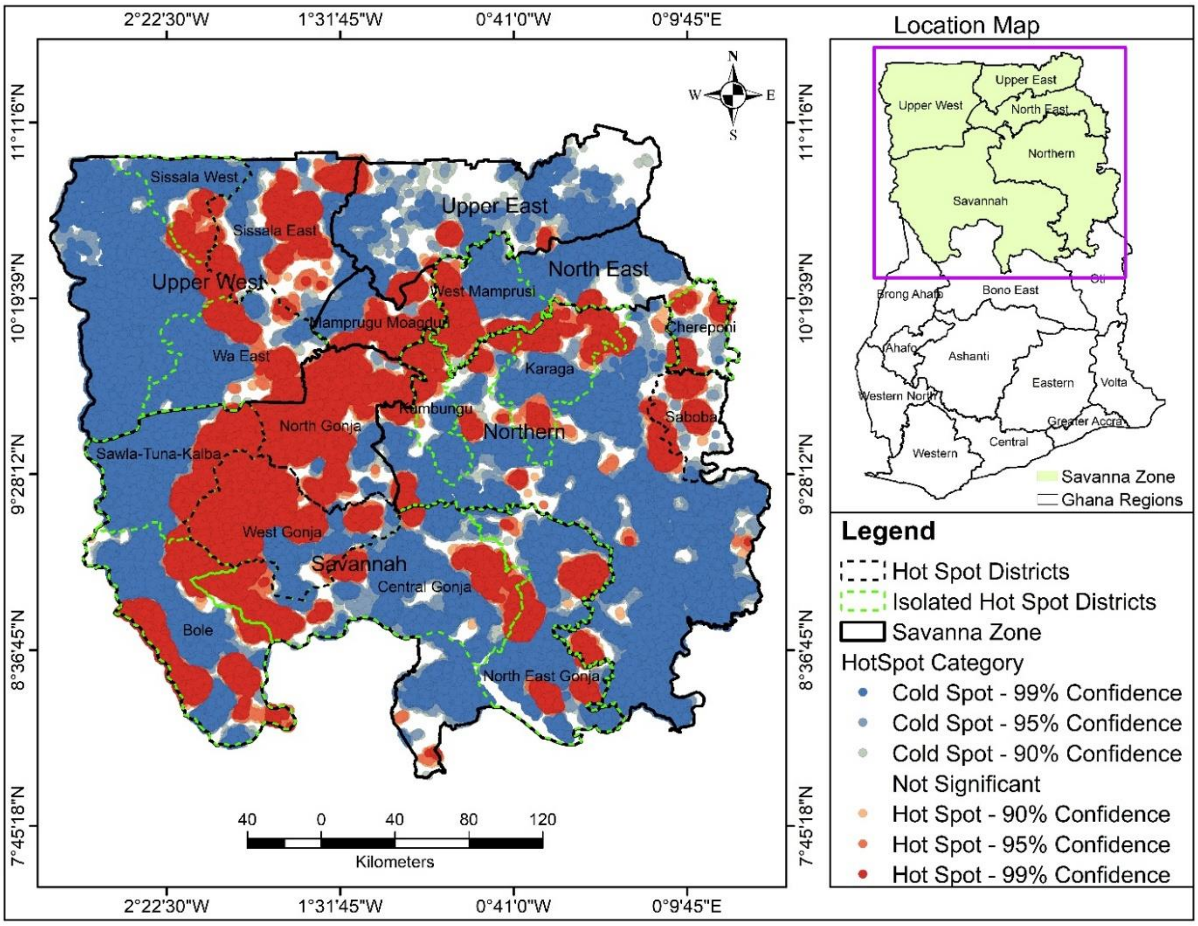

Figure 30: Spatial distribution of hot spot, cold spot, and non-significant FRP cluster: MODIS Active fire and thermal anomaly data; Accessed: https://firms.modaps.eosdis.nasa.gov/

3.4.6. *Environmental and Climatic Predictors of Wildfire Occurrence in Northern Ghana*

This section evaluates all possible combinations of the explanatory variables with burn area as the dependent variable, looking for Ordinary Least Square (OLS) models that best explain the key drivers of wildfires in the Savannah zone. After successfully combining all 14 exploratory variables identified from the climate and environment data, a combination of five exploratory variables (distance to settlements, slope, distance to road, maximum temperature, and elevation) was found to have relatively higher performance (***see Table 11***). The table also presents the regression analysis results assessing the relationship between wildfire occurrence and multiple environmental variables (settlements, slope, distance to road, maximum temperature, and elevation).

The Adjusted R^2 value, which accounts for the number of predictors and adjusts for overfitting, remains consistently at 0.92 across all models. Unlike R^2, Adjusted R^2 only increases when an additional variable provides meaningful explanatory power. The stability of Adjusted R^2 across all three models suggests that the selected variables, distance to settlements, slope, distance to road, maximum temperature, elevation, and land use/cover, are sufficient to model wildfire occurrence effectively without unnecessary predictors.

Although Adjusted R^2 remains the same across models, the differences in the Akaike Information Criterion corrected (AICc) for small sample sizes provide a more refined basis for model selection. The AICc was used for model selection to balance model fit and complexity while adjusting for small sample sizes. Unlike Adjusted R^2, which focuses solely on goodness-of-fit, AICc penalises excessive model complexity, ensuring that only meaningful predictors are retained. In this analysis, AICc values were used to compare the different models. The use of AICc reinforces that the selected model is not only a good fit but also avoids overfitting, making it the most parsimonious choice for understanding wildfire dynamics in Northern Ghana. The assumption underlying AICc is that the residuals are normally distributed and independent and that the model being compared is within a set of candidate models that reasonably describe the data.

The variance inflation factor (VIF) values, ranging from 3.45 to 3.94, confirm no severe multicollinearity among the predictor variables. Since VIF values below 5 indicate low to moderate multicollinearity, there is no severe multicollinearity among the predictor variables, suggesting that the models' estimates are stable and reliable. The consistently low values of the

Jarque-Bera (JB) test (0.03 to 0.05) further support the assumption that the residuals follow a normal distribution, which is crucial for making reliable statistical inferences.

Overall, the high Adjusted R^2 values across models indicate that the explanatory variables provide a strong fit to the data, while the AICc values reinforce the selection of the first model as the most efficient in explaining wildfire patterns. Including distance to road and elevation appears to be crucial in improving model performance, while land use/cover provides minor explanatory value. The stability of these results across different model configurations highlights the robustness of the selected predictor variables in understanding wildfire dynamics in Northern Ghana.

Table 11. Model Comparison for Predictor Variables Impacting Wildfire Occurrence

Variables	AdjR²	AICc	JB	VIF
+Distance to settlements +Slope -Distance to road +Maximum temperature +Elevation	0.92	311.78	0.05	3.45
+Distance to settlements +Slope +Maximum temperature +Elevation +Land use/cover	0.92	311.93	0.05	3.94
+Distance to settlements +Slope -Distance to road +Maximum temperature +Land use/cover	0.92	312.37	0.03	3.48

When comparing the variables, the first model (Distance to settlements, Slope, Distance to road, Maximum temperature, Elevation) has the lowest AICc value (311.78), making it the best fit while maintaining simplicity. It suggests that road proximity may influence wildfire dynamics. The second model, however, replaces Distance to road with Land use/cover, leading to a slight increase in AICc (311.93), implying that while land use/cover is relevant, it does not improve the model significantly.

The third model (Distance to settlements, Slope, Distance to road, Maximum temperature, Land use/cover) excludes Elevation, resulting in the highest AICc value (312.37). This suggests that elevation contributes to explaining variance in wildfire occurrence.

Hence, all three models demonstrate strong predictive performance with high Adjusted R^2 values and normal residual distributions. The first model ***(Distance to settlements, Slope,***

Distance to road, Maximum temperature, Elevation) is slightly superior based on AICc, suggesting that these factors are the most influential in explaining wildfire patterns. The low VIF values also indicate that the predictor variables are not highly collinear, ensuring robust coefficient estimates.

Ordinary Least Square (OLS) Regression Analysis of Wildfire distribution and occurrence in Northern Ghana

The regression analysis results provide insights into the significance and influence of environmental and climatic factors on wildfire occurrence in Northern Ghana. The model's **intercept** (0.085) is not statistically significant ($p = 0.498$) since it is much higher than the standard significance threshold (0.05), suggesting that when all predictor variables are set to zero, the baseline wildfire occurrence is not meaningfully different from zero. The lack of significance is likely because a scenario where all predictors (distance to settlements, slope, distance to roads, maximum temperature, elevation, and land use/cover) are zero is not realistic in the study area. For example, a "distance to settlement" of zero implies a fire starting directly within a settlement, while a maximum temperature of zero is not physically possible in this climate. The high p-value further suggests that wildfire occurrence is primarily influenced by specific environmental and climatic factors rather than an inherent baseline level of wildfire activity. Since the key predictor variables adequately explain the variation in wildfire occurrence, the intercept does not carry strong explanatory power in this model.

Among the predictor variables, **distance to settlements** (coefficient = 0.001, $p = 0.014$) has a positive and statistically significant effect on wildfire occurrence. This indicates that as the distance from settlements increases, the likelihood of wildfire occurrence also increases likely due to human-induced ignition sources such as land clearing and farming activities. This suggests that areas farther from human settlements may have lower fire suppression activities, allowing wildfires to spread more freely. **Slope** (coefficient = 1.641, $p = 0.018$) is also positively associated with wildfire occurrence, suggesting that areas with steeper slopes experience more fire activity. This may be due to changes in vegetation distribution, fuel accumulation, and fire behaviour in sloped landscapes. This implies that fires spread more rapidly on steeper slopes due to the upward movement of heated air, which preheats and dries fuel ahead of the fire front

Maximum temperature is the strongest predictor in the model (coefficient = 1.180, $p < 0.001$), with a highly significant impact on wildfire occurrence. The positive relationship indicates higher temperatures contribute to increased wildfire activity, likely due to drier conditions that enhance fuel combustibility. Similarly, **distance to roads** (coefficient = 0.000, p = 0.613), elevation (coefficient = 0.008, p = 0.448), and land use/cover (coefficient = 0.033, p = 0.927) are not statistically significant predictors, as their p-values exceed the 0.05 threshold. The insignificant effect of distance to roads suggests that proximity does not strongly influence wildfire occurrence in the study area, potentially due to mixed effects of human activities such as ignition sources and fire suppression. Also, **elevation** and **land use/cover** do not exhibit strong individual effects on wildfire dynamics. This indicates that their role may be more context-dependent or interact with other variables influencing fire behaviour.

The **standard error** measures the variability in the coefficient estimates. More minor standard errors, such as that for distance to settlements (0.000), indicate more precise estimates, while more significant standard errors, as seen **for slope (0.943) and land use/cover (0.383),** suggest more significant uncertainty in their estimated effects. If standard errors were higher, the confidence in the estimated impact of these variables would decrease.

The **t-statistic** evaluates the strength of the relationship between each predictor and wildfire occurrence. A high absolute t-value strongly influences maximum temperature (t = 10.966). At the same time, lower values, such as for the distance to road (-0.377) and land use/cover (0.086), suggest weak or negligible effects. This is closely linked to the p-value, which determines statistical significance. Predictors with **p-values** below 0.05, such as distance to settlements (p = 0.014) and slope (p = 0.018), are statistically significant, implying that they have a meaningful impact on wildfire occurrence. Variables with high p-values, such as elevation (p = 0.448) and land use/cover (p = 0.927), do not significantly explain wildfire patterns. The **variance inflation factor (VIF)** values range from 1.892 to 4.062, indicating low to moderate multicollinearity. Maximum temperature has the highest VIF (4.062), but multicollinearity is not a significant concern in the model since it remains below the common threshold of 5. This confirms that the predictor variables provide relatively independent contributions to explaining wildfire occurrence without severe redundancy. Although wildfires are often ignited near roads, the findings suggest that road networks may act as firebreaks, limiting fire spread rather than increasing burn area. The Variance Inflation Factor (VIF) values for all predictor variables were below 7.5, indicating no significant multicollinearity issues in the model.

Overall, the results highlight that distance to settlements, slope, and maximum temperature are the key drivers of wildfire occurrence in Northern Ghana. The strong effect of maximum temperature emphasises the role of climatic factors in shaping fire dynamics. At the same time, the influence of distance to settlements and slopes underscores the importance of human and topographic factors. The lack of significance for distance to roads, elevation, and land use/cover suggests that these factors may have a weaker or more complex relationship with wildfire occurrence in the region.

Table 12. Coefficient Estimates and Diagnostic Statistics for Variables Impacting Wildfire Occurrence

Variable	Coefficient	StdError	t-Statistic	Probability	VIF
Intercept	0.085	1.896	0.045	0.498	
Distance to settlement	0.001	0.000	2.552	0.014	3.499
Slope	1.641	0.943	2.456	0.018	1.892
Distance to road	0.000	0.000	-0.377	0.613	3.435
Maximum temperature	1.180	0.108	10.966	0.000	4.062
Elevation	0.008	0.011	0.728	0.448	2.743
Land use/cover	0.033	0.383	0.086	0.927	3.076

statistically significant p<0.05, statistically significant p<0.01, variance inflation factor (VIF) value <7.5

Model Performance and Diagnostic Tests

The model diagnostic tests in ***Table 13*** below assess the overall reliability, consistency, and predictive accuracy of the OLS regression model used to analyse wildfire occurrence in the Savannah zone of Ghana. The ANOVA test returned statistically significant Joint F-Statistic (106.69, $p < 0.01$) and Joint Wald Statistic (9214.26, $p < 0.01$), confirming that the independent variables collectively explain a significant proportion of the variance in wildfire occurrence. The Koenker (BP) Statistic (4.593, $p = 0.597$) was not statistically significant, implying that the relationships between the explanatory variables and the dependent variable are consistent across the study area, validating the model's robustness in capturing wildfire drivers. Finally, the Jarque-Bera Statistic (5.99, $p = 0.050$) was non-significant at $p < 0.01$, indicating that the model’s residuals follow a normal distribution, confirming that the model is bias-free.

Table 13. Summary of Model Diagnostic Test Statistics

Parameters	Values	P-value
Joint F-Statistic	106.690039	0.000000
Joint Wald Statistic	9214.257822	0.000000
Koenker (BP) Statistic	4.593075	0.596957
Jarque-Bera Statistic	5.993662	0.049945

Statistically significant $p < 0.01$, $R^2 = 0.930247$, Adjusted $R^2 = 0.921528$, AICc = 314.517620

These diagnostic results, along with an R^2 (0.930) and high Adjusted R^2 (0.922), indicate that the model explains 92% of the variation in wildfire occurrence, making it a strong predictive tool for assessing fire risk. The Akaike Information Criterion (AICc = 314.52) also suggests a well-fitted model.

Geographically Weighted Regression (GWR)

Using the same dependent variable (burn area) and the six explanatory variables (including distance to settlements, slope, distance to road, maximum temperature and elevation) as the OLS model, a GWR model was fitted using the fixed kernel and AICc bandwidth calibration. The results suggest that similar to the OLS model, there was no multicollinearity problem in the local regressions, as the condition number for each regression was below 30. The calibrated GWR results further suggest a slight improvement in the global model. Comparing both models with the AICc values shows that the value was reduced by 2.737982, i.e., from 314.517620 in OLS to 311.779638 in GWR. This implies that the GWR model's fitness is pretty high when explaining the key drivers of wildfire (burn area) because it had the smallest AICc value. Both the OLS and GWR models can explain over 90% of the key drivers of wildfires (burn area) in the Savannah zone of Ghana in terms of their adjusted R^2 values (see Table 14).

The OLS linear regression model revealed that about 92 percent (Adjusted R2 = 0.921528) of wildfires occur and spread with Akaike's Information Criterion (AICc) = 314.517620 (see ***Table 14***).

Table 14. Comparison of GWR and OLS Model Performance Metrics

Parameters	Fitted GWR	OLS	Difference
AICc	311.779638	314.517620	-2.737982
R^2	0.930256	0.930247	0.000009
Adjusted R^2	0.923120	0.921528	0.001592

3.5. DISCUSSION

3.5.1. Wildfire Effects on Demographic Composition and Livelihoods

Wildfires significantly impact communities in Northern Ghana, where agriculture is not just a means of livelihood but a way of life. The demographic structure of these communities, especially gender, age, and occupation, affects their vulnerability to wildfire risks.

Demographic Composition and Wildfire Vulnerability

The demographic characteristics of the surveyed communities in Northern Ghana reflect a firm reliance on agriculture, with 70% of respondents engaged in farming activities. The study tested the hypothesis. The Pearson correlation analysis showed a significant positive relationship ($r = X$, $p < 0.05$) between agricultural expansion and fire frequency, supporting the alternative hypothesis (H_{11}). These findings indicate that land use changes, mainly through farming and charcoal production, are key to fire occurrences. The proximity of wildfires to settlement areas further reinforces the role of anthropogenic ignition sources. The gender distribution was relatively balanced, with 55% male and 45% female respondents. This composition is significant, as both men and women are directly involved in land-based activities such as farming and the collection of resources. However, gender roles within the household and community affect their exposure to and capacity to recover from wildfire-related damage. Studies have shown that gender-specific roles influence how wildfires affect different groups. For instance, women in rural communities often have more limited access to resources, exacerbating their vulnerability to disasters such as wildfires (Smith et al., 2019). In Ghana, women are typically responsible for collecting firewood, which increases their exposure to wildfires during the dry season (Owusu et al., 2021). These gendered roles mean that, while both men and women are affected, women may face additional challenges in coping with wildfire impacts.

Livelihoods, Economic and Social Impacts of Wildfires and the Role of Agriculture

Agriculture plays a vital role in people's livelihoods in the Savannah zone. The study revealed that a substantial portion of the population depends on farming, with over 70% of respondents directly engaged in this sector. This reliance makes communities vulnerable to wildfires, frequently destroying crops, farmland, and important natural resources. According to the respondents, 64% mentioned that wildfires had the most severe impact on forests and farmlands, underscoring the economic risks such incidents pose to the agricultural sector.

Wildfires in the Savannah zone are not isolated incidents but occur regularly during the dry season. The destruction of farmlands has led to reduced crop yields and income loss, particularly for subsistence farmers. In similar contexts, wildfires have been found to diminish soil fertility, further reducing agricultural productivity in the long term (Kalame et al., 2014). For instance, in West Gonja, where wildfire hotspots were identified, farmers reported significant income losses due to burned fields (Dahan & Kasei, 2022). The economic impact of wildfires extends beyond direct crop loss. Wildfires also disrupt market access, labour availability, and the broader local economy. As noted by several respondents, the loss of agricultural land means that farming households cannot produce surplus crops for sale, affecting their purchasing power. This is consistent with findings by Bowman et al. (2017), who noted that wildfire-induced poverty traps occur when affected households are forced to sell off assets to survive after a disaster. The social impacts of wildfires are also evident in the disruptions to daily life and long-term community stability. Wildfires have been linked to forced migrations in some parts of Northern Ghana, where entire families relocate after losing their homes and farmlands to fires (Appiah et al., 2021). In addition, educational institutions and healthcare services may be disrupted, further compounding the social vulnerability of these populations.

3.5.2. Spatiotemporal Dynamics of Wildfire Patterns

Wildfire occurrences in Northern Ghana's Savannah zone have exhibited distinct spatial and temporal variations over the past two decades. Analysing wildfire trends from 2000 to 2021 offers some critical insights into what drives wildfire activity, how effective management strategies have been, and the impacts of climate variability on these fires.

Trends in Wildfire Occurrences and Burned Areas

Over the 21 years, approximately 432,153 active fires were recorded, covering an area of about 515,822.7 km². The annual trends in wildfire activity show significant fluctuations, with increments noted in 2005, 2010, and 2015. There was a notable decline after 2020. Remarkably, 2011 saw the highest number of active fires, at around 28,943, while in 2002, the largest burned area covered nearly 33,883.4 km². Several climatic and environmental factors, such as high temperatures, strong winds, and low humidity levels, could have led to increased fires observed in 2005, 2010 and 2015. These weather conditions align with the findings from (Bowman et al., 2017), highlighting the significant role of climate variability in wildfire occurrences. However, the noticeable drop in wildfire cases after 2020 hints that other factors might be helping reduce fire impacts. Improved fire management strategies, such as community-based prevention initiatives and establishing firebreaks within some Savannah areas, have likely contributed to the reduction (Dahan & Kasei, 2022). Equally promising are the changes in land use involving converting once-increased fire-prone regions into farmlands. This shift in land use has the potential to significantly reduce available dry vegetation, offering hope for further decreasing the occurrences of wildfire.

Weather patterns play a significant role in influencing fire occurrences on a monthly and seasonal basis. The dry or vegetation-burning season typically falls between December and February, when most forest wildfires occur. This observation aligns with the work of Kouassi et al. (2022), who noted that in West Africa, the dry season increases fire events. Understanding these weather patterns is crucial in planning and implementing effective fire management strategies. It is crucial to note that wildfires occur very little in the wet season (June—October) due to high rainfall, which increases the moisture content of vegetation, making it difficult for fires to start (N'Dri et al., 2018). This observation underscores the importance of planning fire management activities considering the seasonal variability in fire risk and weather patterns, ensuring that strategies are adaptive and effective. Several studies have observed downward trends in the number of wildfires and burnt areas in sub-Saharan Africa in recent years (Kugbe et al., 2012), (Dwomoh & Wimberly, 2017b), (N'Datchoh et al., 2015), (Jiang et al., 2020), (Machete & Dintwe, 2023) supporting the results of this study.

3.5.3. Influence of Climatic Variability and Land Use Changes on Fire Dynamics

Wildfires in Northern Ghana's Savannah exhibit a fascinating relationship with climatic conditions. The Mann-Kendall trend analysis reveals a noticeable reduction in burned areas over the period ($p = 0.015$). Such trends are intriguing and might be influenced by declining temperatures and fluctuating precipitation patterns noted in specific years. Jolly et al. (2015) state that precipitation and humidity levels are critical in reducing wildfire risks. They increase the moisture content of vegetation, thus limiting the likelihood of fire ignition. The years with higher wildfires (2005 and 2010) coincide with periods with below-average rainfall, particularly in the dry season. The dry soil during such periods appears to set the stage for extensive wildfires, echoed by Shekede et al. (2021), who found prolonged dry spells escalating fire risks within Savannah ecosystems. The hypothesis (**H_{02}**) that climate change (rising temperatures, reduced humidity) does not significantly contribute to wildfire frequency and intensity in northern Ghana was tested using Ordinary Least Squares (OLS) Regression. The results showed that increased temperatures and reduced humidity levels were significantly correlated ($\beta = X$, $p < 0.05$) with higher fire frequencies, leading to the rejection of H_{02} and supporting H_{12}. The high

Adjusted R^2 (0.922) in the OLS model indicates that the selected independent variables explain 92.2% of the variance in wildfire occurrence. This strong model performance suggests that key factors such as vegetation cover, temperature variations, wind speed, relative humidity, and anthropogenic influences (e.g., land use changes, agricultural expansion, and settlement growth) are reliable predictors of wildfire dynamics in the study area. The statistically significant Joint F-Statistic (106.69, $p < 0.01$) and Joint Wald Statistic (9214.26, $p < 0.01$) reinforce that these explanatory variables collectively contribute meaningfully to the model's ability to predict fire occurrences. Furthermore, the Koenker (BP) Statistic ($p = 0.597$) confirms that the relationships between these independent variables and wildfire occurrence remain consistent across the study area, implying that wildfire drivers behave similarly across different ecological zones within the Northern Ghana savanna. This consistency is particularly relevant for policymakers and land managers as it suggests that fire management strategies could be applied uniformly across the region without significant regional variations in fire response patterns. The Jarque-Bera test ($p = 0.050$) further supports the validity of the model by indicating that the residuals follow a normal distribution. This reduces concerns about bias and reinforces the reliability of the findings.

These findings align with studies in other savannah ecosystems that have identified climatic conditions and human-induced activities as primary drivers of fire regimes in fire-prone ecosystems. Higher temperatures combined with a lack of precipitation significantly increase fuel dryness and flammability, promoting more frequent and intense wildfires and hence increasing the total areas of a place (N'Datchoh et al., 2015). According to (Abatzoglou and Williams, 2016) and (Turco et al., 2016), the fuel of living and dead plants became much drier due to the rise in temperature, vapour pressure deficit, and lack of precipitation. Wildfires and burnt areas were found to be positively impacted by temperature (Koutsias et al., 2013). (Mike D. Flannigan et al., 2009) cited research that found temperature to be the most important factor in wildfires.

Land cover changes have an evident influence, such as the expansion of agriculture and establishment of settlements on wildfire activities. In the Geographically Weighted Regression (GWR) analysis, distance from settlements was found to be statistically significant ($p < 0.05$). The closer to human activities, the higher the risk of suffering wildfires. This is similar to the findings of Stolle et al. (2003), who noted that human interventions like land clearing and slash-and-burn cultivation contribute to wildfires in the tropics. Additionally, it can be assumed that since 2020, there have been changes in land cover, in which increased agricultural development and land improvements may be a factor that has resulted in fewer fires. With the change in vegetation cover and an increase in the cultivated areas, the quantity of biomass available for burning decreases, thus likely reducing fires. In the West Gonja area, designated as a wildfire hotspot, firebreaks and agricultural burning control measures implemented locally have successfully restrained fire outbreaks (Dahan & Kasei, 2022).

3.5.4. Spatial Distribution of Wildfire Hotspots

The Fire Radiative Power (FRP) from satellite data, used to carry out the hotspot analysis throughout 2000-2021, detects several critical zones with very high wildfires. Most importantly, specific areas within the West Gonja and Mamprugu Moagduri Districts have been singled out as fire-prone even within the peak of the dry season due to the high FRP. Dahan and Kasei, 2022, have also observed this spatial distribution of fires within specific areas. They argue that settlement proximity, land use, and land cover are important determinants of fire occurrence and spread. The dry Savannah landscape, with its limited woody vegetation and grass cover, creates sufficient forest fire fuel, especially in the dry season when the moisture content of vegetation is low (Bowman et al., 2017). Understanding these factors is crucial for effective fire management and prevention strategies, and your role in this process is vital and empowering.

wildfire cold spots, or areas with fewer fire occurrences, were predominantly observed in all districts of the Upper East region of Ghana. The non-significant clusters of cold spots scattered across the Savannah landscape could be due to localised variations in these factors or the presence of small-scale fire breaks or barriers that limit fire spread (Munyaradzi Davis Shekede et al., 2021), (Asori & Appiah, 2021). The spatial patterns of wildfires across the Savannah landscape of Ghana highlight the need for targeted fire management strategies and policies tailored to specific regions and their fire regimes. Identifying regions prone to frequent wildfires, such as West Gonja and Mamprugu Moagduri, is pivotal in crafting impactful fire control measures. Wildfires frequently rage through these districts, endangering residents' well-being and local flora and fauna diversity. The agricultural community faces significant setbacks as fires often decimate crops, jeopardise food supplies, and shake economic stability. The human and economic toll of these fires is immense, and it is crucial that we act to prevent such devastation. Furthermore, continuous fires wreak havoc on vital ecosystems, uncovering the Savannah's ability to bounce back from other environmental upheavals. Hotspot areas may require more intensive fire prevention and suppression efforts, while cold spot areas could serve as models for effective fire management practices. To achieve the core objectives of reducing vulnerabilities and community resilience, there is a need to carry out further studies on the current topic to identify most of the key drivers of wildfires in the region from a modelling perspective and also develop some nature-based solutions frameworks on wildfires as mitigation measures that could clearly state the fundamental determinants of wildfires, and predict the future trajectory of fire patterns in the region.

3.5.5. Seasonal Trends and Timing of Interventions

Timing is essential for good fire management because wildfires in the Savannah area of Northern Ghana usually occur during certain times of the year. The difference in fire seasonality over the years can be explained by the distinct characteristics of early and late dry season fire periods (N'Datchoh et al., 2015). Wildfires peak during the dry season, especially around December through February, because of high temperatures mixed with low rainfall and stronger winds, making fires more likely. To lower these seasonal dangers, proactive fire management strategies are often necessary rather than reactive ones. For example, controlling burns earlier in the dry season when vegetation might be moist can help reduce fuel availability and prevent larger fires later on (Shekede, 2021). Local firefighting teams must receive training before the dry season kicks off to ensure they can respond quickly if any fires break out suddenly. In line with (Owusu-Ofori et al., 2021) found that establishing firebreaks in high-risk areas can significantly reduce the spread of wildfires. In regions like Mamprugu Moagduri, where wildfires frequently threaten farmlands, firebreaks could serve as a first line of defence. In addition, local communities in West Gonja and other hotspot areas should be actively involved in fire prevention and monitoring. By setting up early warning systems that leverage traditional knowledge and modern technologies such as satellite data, communities can detect fires early and respond before they escalate (Kouassi et al., 2022).

However, numerous opportunities exist to leverage technological advancements in fire management and monitoring. By continuously monitoring fire activity throughout the Savannah region, satellite-based systems like MODIS (Moderate Resolution Imaging Spectroradiometer) offer up-to-the-minute information that can be utilised to focus fire management efforts on the most at-risk spots (Giglio et al., 2018). The integration of these resources with local knowledge and expertise holds the potential to mitigate some of the challenges associated with handling fires in remote areas, offering a hopeful position for the future of fire management in Northern Ghana.

3.6. CONCLUSION

This study provides valuable insights into the spatiotemporal dynamics and key drivers of wildfires in the Savannah ecological zone of Ghana from 2000-2021, with a total of 432,153 active fires burning 515,822.7 km2 of vegetation over the 21 years, with the highest occurrence in 2011 (28,943 fires) and most significant burn area in 2002 (33,883.4 km2). Spatial regression analysis identified climatic factors (maximum temperature), vegetation (land use/cover), topographic factors (slope, elevation), and anthropogenic factors (distance to settlements, distance to roads) as key drivers of wildfire occurrence and distribution. The Ordinary Least Squares (OLS) regression showed that distance to settlements, slope, maximum temperature, elevation, and land use/cover were positively correlated with burn area. In contrast, distance to roads was negatively correlated. Also, distance to settlements and slope was statistically significant at $p<0.05$, while the maximum temperature at $p<0.01$, indicating their importance as key drivers of wildfires and associated burn areas in the Savannah zone. The findings highlight the importance of considering climatic, vegetation, topographic, and anthropogenic factors in understanding and managing wildfire occurrence and distribution in the region. The decreasing trend in burn areas over time suggests some progress in wildfire management. Still, the persistent clustering of active fires in certain districts indicates the need for targeted interventions in these hotspot areas. The study provides critical insights for effective wildfire management strategies to limit damage and promote ecosystem health in the Savannah zone of Ghana by identifying and addressing the significant biotic and abiotic drivers of wildfire occurrence and distribution.

CHAPTER FOUR:

FIRE EFFECTS ON WOODY SPECIES COMPOSITION, DIVERSITY, VEGETATION STRUCTURE, AND LAND COVER CHANGES IN GHANA'S NORTHERN SAVANNAH ECOSYSTEM

Part was published: Wildfire Impacts on Species Composition, Land Use Dynamics, and Ecosystem Service Vulnerability in Northern Ghana's Savannah Ecoregions **https://journalijecc.com/index.php/IJECC/article/view/4723**

4. ABSTRACT

Wildfires play a crucial role in shaping the composition, diversity, and structure of Savannah ecosystems in Ghana. This study assesses how wildfires affect woody species composition, vegetation dynamics, and ecosystem services within Ghana's northern Savannah regions by focusing specifically on how often fires occur and how intense they are. Using a combination of field surveys, remote sensing techniques, and statistical analyses, this research examines 30 areas with different fire risk levels to pinpoint which species thrive in fire-prone environments and are vulnerable under frequent burning conditions. A total of 123 woody species from 102 genera and 38 families were identified, with Fabaceae emerging as the most dominant family. The results indicated that fire-tolerant species like *Vitellaria paradoxa* and *Parkia biglobosa* were prevalent in regions prone to fires. Microphanerophytes and therophytes were found to be the predominant life forms in frequently burned areas. The study also highlighted the complex interactions between fire regimes, human activities, and environmental gradients in shaping Savannah plant communities. Canonical Correlation Analysis identified three distinct plant communities based on fire frequency and anthropogenic disturbances. The results highlight the importance of fire as a critical driver of Savannah's ecosystem dynamic. They should be considered in fire management strategies for their ecological advantages of fires, preserving biodiversity, and sustainable land utilisation. Given the significant influence of fire frequency on woody species composition and structural diversity, fire management policies should integrate controlled burning practices and community-based fire prevention strategies to mitigate biodiversity loss while maintaining ecosystem resilience.

Key Words: Wildfire dynamics, Savannah ecosystems, Species composition, Vegetation structure, Fire frequency

4.2. INTRODUCTION

Background and Problem Statement

Wildfires play a key role in regulating vegetation structure, nutrient cycling, and species adaptation across different biomes ranging from the boreal forests of North America and Eurasia to the Mediterranean woodlands, Australian bushlands, and African savannahs (Bowman et al., 2009). However, changing fire regimes due to anthropogenic activities and climate change increasingly alter these ecosystems, sometimes devastatingly.

In North America, for example, the frequency and severity of wildfires in the western United States have surged due to prolonged droughts, rising temperatures, and increased fuel loads resulting from decades of fire suppression (Abatzoglou & Williams, 2016). Similarly, in the Amazon rainforest, widespread deforestation combined with seasonal droughts has heightened fire susceptibility, leading to significant carbon emissions and biodiversity loss (Cochrane, 2002). The Mediterranean region also faces escalating wildfire threats, exacerbated by extreme heat waves and changes in land-use patterns that have increased fuel availability (Pausas & Keeley, 2009).

African savannahs, characterised by a co-dominance of trees and grasses, cover vast areas of the tropics and subtropics and are among the most fire-prone landscapes in the world, with wildfires occurring regularly across sub-Saharan Africa (Sankaran et al., 2005). These fires, whether naturally ignited by lightning or human-induced land clearing, play a critical role in maintaining the balance between woody vegetation and grasslands (Sankaran et al., 2005). However, increased fire frequency and intensity driven by agricultural expansion, overgrazing, and climate variability disrupt this balance. Repeated burning can degrade soil quality, reduce tree cover, and alter species composition, leading to long-term shifts in savannah ecosystem dynamics (Bond & Keeley, 2005).

In Ghana, Savannahs (approximately 65% of Ghana's land area) (Sankaran et al., 2005) are not only ecologically significant but also economically vital, supporting the livelihoods of millions through agriculture, livestock grazing, and the provision of ecosystem services (Kojo Sebastian Amanor, 2002). Fire has been an integral component of Ghana's Savannah ecosystem for millennia, influencing its structure, composition, and function. (Swaine, 1992). Both natural and anthropogenic fires have historically played a role in shaping these landscapes, with human-induced fires becoming increasingly dominant in recent centuries (Laris, 2002). However, wildfires have become more frequent and severe, posing a significant threat to biodiversity, ecosystem services, and local livelihoods. Studies indicate that approximately 30% of Ghana's land area is prone to wildfires, with the savannah zone particularly vulnerable (GNFS, 2022). Recent satellite imagery suggests that depending on the year and vegetation type, between 25% and 80% of the wooded savannah in West Africa burns annually (Paul Laris, 2002). The relationship between fire and Savannah ecology is complex, with fire acting as a destructive and regenerative force. It can eliminate fire-sensitive species, promote fire-adapted taxa, alter competitive dynamics, and shape the overall physiognomy of the landscape (Higgins et al., 2007).

Climate change is expected to significantly influence fire regimes in Ghana's Savannah. Ghana's average temperature has increased by 1°C since 1960, with projections indicating a 1.0–2.8°C rise by 2060 (McSweeney et al., 2010). These warming trends and shifting precipitation patterns prolong dry seasons and fuel loads, creating conditions conducive to more frequent and intense wildfires. These changes could potentially alter the balance of woody and herbaceous vegetation (Scheiter & Higgins, 2009). These changes could have far-reaching consequences for Savannah's ecology and management.

Beyond ecological effects, wildfires in Ghana's savannah have profound socio-economic implications. Farmers practising rain-fed agriculture are particularly vulnerable, as uncontrolled fires can destroy crops, grazing lands, and economically valuable trees such as *Vitellaria paradoxa* (shea) and *Parkia biglobosa* (dawadawa), impacting food security and household incomes (Pouliot, 2012; Antwi-Agyei et al., 2018). Additionally, repeated fires lead to air quality deterioration, increasing the risk of respiratory diseases among local populations (Johnston et al., 2012). In addition, Land degradation due to overgrazing, agricultural expansion, and unsustainable harvesting of wood resources is a growing concern (P. K. Boateng, 2017) coupled with the changes in traditional land management practices, including altered fire regimes.

Several studies have been carried out in Ghana on tree-structural diversity; (Appiah et al., 2010; Amissah et al., 2014 & Appiah, 2013) all concentrated in Ghana's forest and transitional zone, with very few concentrated in minimal areas of Northern Ghana. For instance, (Damian et al., 2014) and (Attua & Pabi, 2013) studied the effects and impacts of fire on tree diversity, population, and vegetation structure in the Northern Region of Ghana and the Mole National Park. Although they found that fire frequency influenced species composition and structure, the study was limited in scope. More frequent fires led to lower tree density and diversity.

Considering all the challenges, this current study sought to assess the effects of wildfire on woody species composition, diversity, and vegetation structure in Ghana’s savannah ecosystems. Understanding the effects of fire on woody species composition, diversity, and vegetation structure in Ghana's Savannah is crucial for several reasons. First, it provided insights into the ecological processes that maintain these ecosystems, contributing to our broader understanding of Savannah dynamics. Second, it informed conservation strategies to preserve biodiversity and ecosystem services in the face of changing fire regimes and climate. Third, it has practical implications for land management, including fire use in traditional agricultural systems and rangeland management (Boateng, 2017). This study was conducted in 5 categorised areas based on the frequency of wildfire occurrences provided by MODIS data: very high, high, medium, low, and very low.

4.2.1. Objectives and Hypotheses

The main objective of this study was to assess the effects of wildfires on savannah ecosystems’ structural and vegetation dynamics, including woody species composition, diversity, and vegetation structure and their impact on land cover changes in the savannah ecosystems of northern Ghana.

Specifically, these objectives helped to achieve the main objective;

1. To assess the impact of different fire regimes on species composition and vegetation structure.
2. To evaluate the relationship between fire frequency, tree cover, and species richness in fire-prone areas
3. To investigate fire-driven vegetation changes and their effects on ecosystem structure

Hypotheses

Hypothesis 1: Fire Regimes and Vegetation Structure

- **H_{01}:** Different fire regimes (low, moderate, high intensity) do not significantly affect species composition and vegetation structure.
- **H_{11}:** Different fire regimes significantly influence species composition and vegetation structure.

Hypothesis 2: Fire Frequency, Tree Cover, and Species Richness

- **H_{02}:** Frequent wildfires do not significantly reduce tree cover or alter species richness in fire-prone areas.

- **H_{12}:** Frequent wildfires reduce tree cover and significantly lower species richness in fire-prone areas.

Hypothesis 3: Fire-Driven Vegetation Changes

- **H_{03}:** Frequent high-intensity wildfires do not significantly alter vegetation structure in fire-prone areas of the northern savannah zone of Ghana.
- **H_{13}:** Frequent high-intensity wildfires promote shrubland expansion and decrease forest cover in fire-prone areas of the northern savannah zone of Ghana.

4.3. METHODOLOGY

The methodology adopted in this research combines ground-based ecological surveys with remote sensing data analysis to provide a comprehensive understanding of wildfire impacts. A two-step approach was adopted to assess the wildfire effects on Savannah woody vegetation: *field data collection* and *remote sensing analysis*. The field data collection included gathering on-site ecological data on plots of land and recording vegetation structure, species composition, and environmental variables. The remote Sensing analysis involved using MODIS NDVI data (2001-2022) to assess large-scale, long-term vegetation cover and health changes. The various methods used for this objective are explicitly outlined in ***Figure 31*** below.

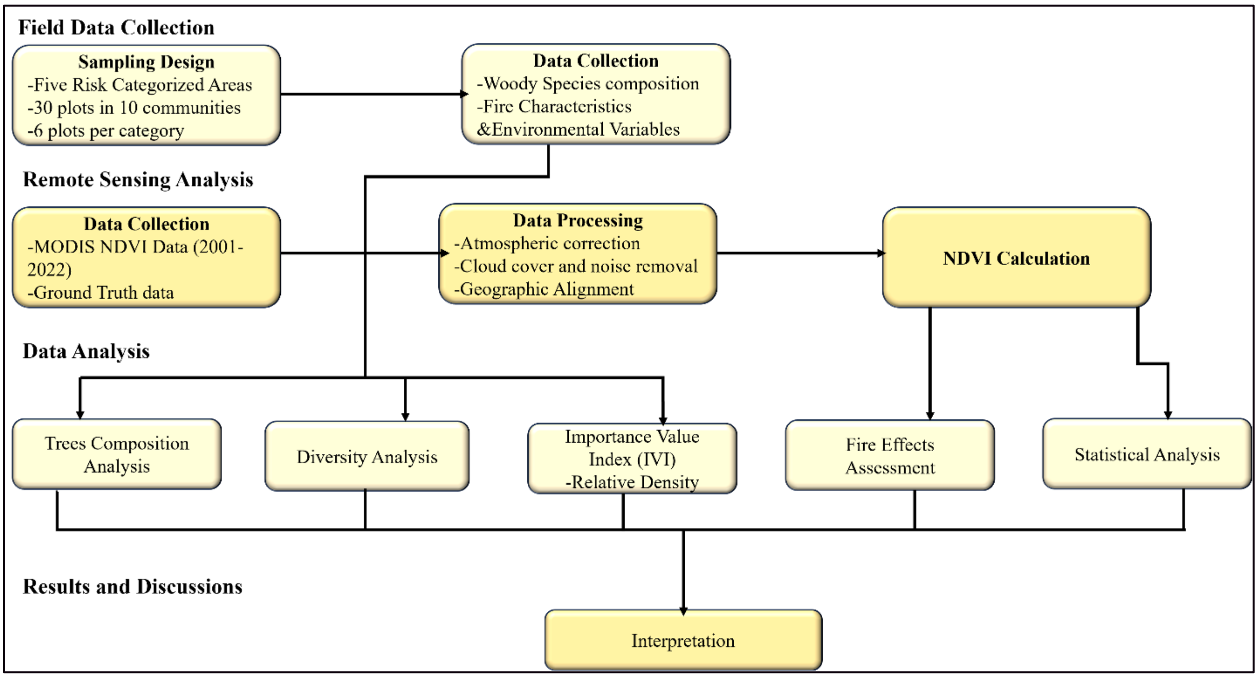

Figure 31: Methodological Framework for Assessing Wildfire Impact on species structural and vegetation dynamics

4.3.1. Sampling Design- Plot Selection and Sampling Approach

To assess fire effects on woody species composition, diversity, and vegetation structure, pure random sampling was employed to select 30 plots across 10 communities: Gbasinkpa, Busunu, Soo, Gushie, Kasaana, Gbal, Siniesu, Gbedembilisi, Bu, and Faalu (***See. Figure 32***). This approach ensured unbiased coverage of vegetation structures within the savannah ecosystem while minimizing selection bias. The geographical extent of each selected community was delineated using GPS surveys, Google Earth, and existing GIS shapefiles. The boundary coordinates of each community were extracted to establish the sampling frame. Within these boundaries, a random number generator was used to select latitude and longitude values. This was done using the RAND () function in Excel that generated random decimal values within each community's latitude and longitude range. The process was repeated until 30 unique coordinate pairs were obtained.

The randomly generated points were imported into QGIS and Google Earth to visualise their spatial distribution across the 10 communities. Points that fell in unsuitable areas, such as water bodies, roads, or settlements, were discarded and replaced with newly generated random coordinates within the same community. A final GPS-compatible dataset was created for field validation, ensuring that the selected plots were accessible and representative of the natural variability within the study area. This randomised selection method ensured that the sampling captured the natural heterogeneity of the savannah ecosystem, preventing biases in plot placement and improving the robustness of species composition and vegetation structure assessments.

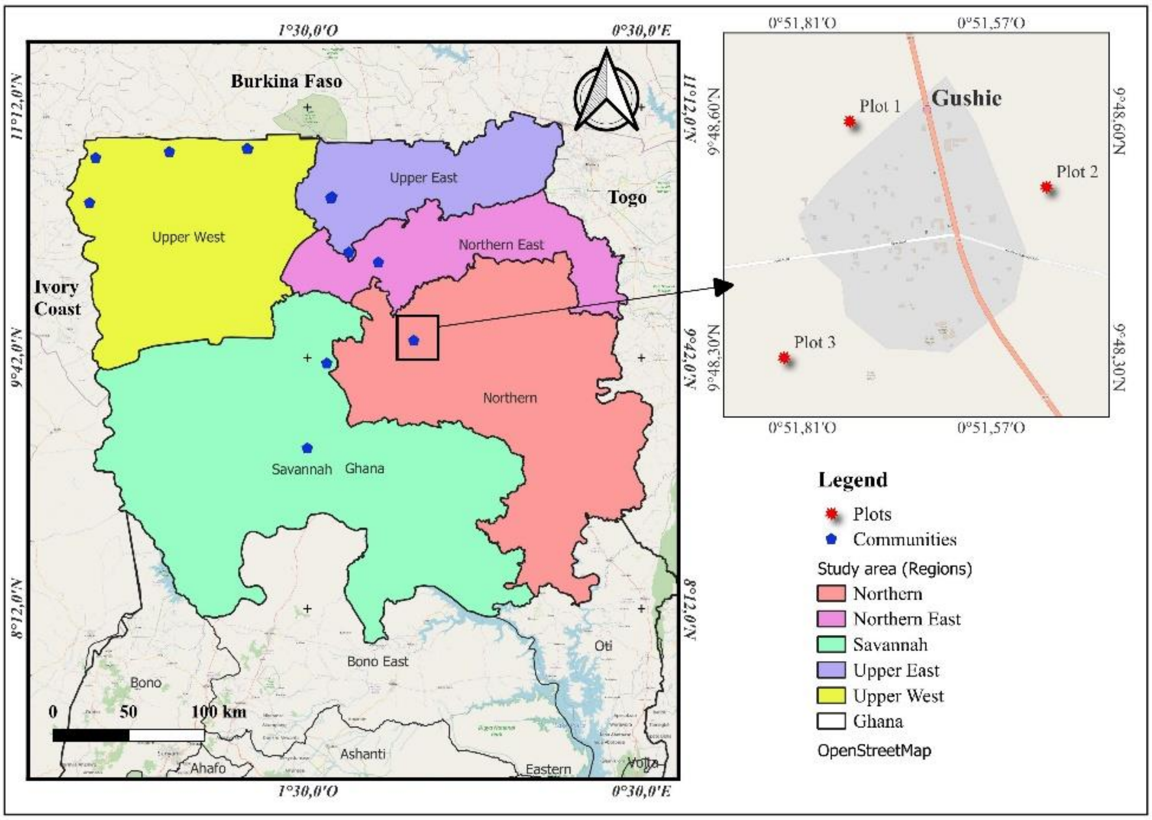

Figure 32: Study area location with an example of a Google image showing how three (3) plots are identified in each community; Source: Ghana Statistical Service (GSS) for administrative boundaries, OpenStreetMap for road networks, and field data collection for study plots.

4.4. DATA COLLECTION

The fire history for each plot was determined using a combination of satellite imagery analysis (MODIS burned area products), field survey GPS data, and interviews with local community members in five categorised areas: very high, high, medium, low, and very low. Inspirations were drawn from previous works by Toko & Sinsin (2011) and Fousseni et al. (2011) conducted in the district of Djidja, located in the Sudano-Guinean zone of Benin and the Sudanian zone of northern Togo, respectively. These areas are characterised by a transition between savannah and forest ecosystems and riparian, featuring a mix of woody and herbaceous vegetation. At each point of the wildfire inventory, 30 permanent plots of 30m x 30m, three subplots of 1x1m, and a subplot of 5x5m were established in 10 communities, as seen in ***Figure 33***.

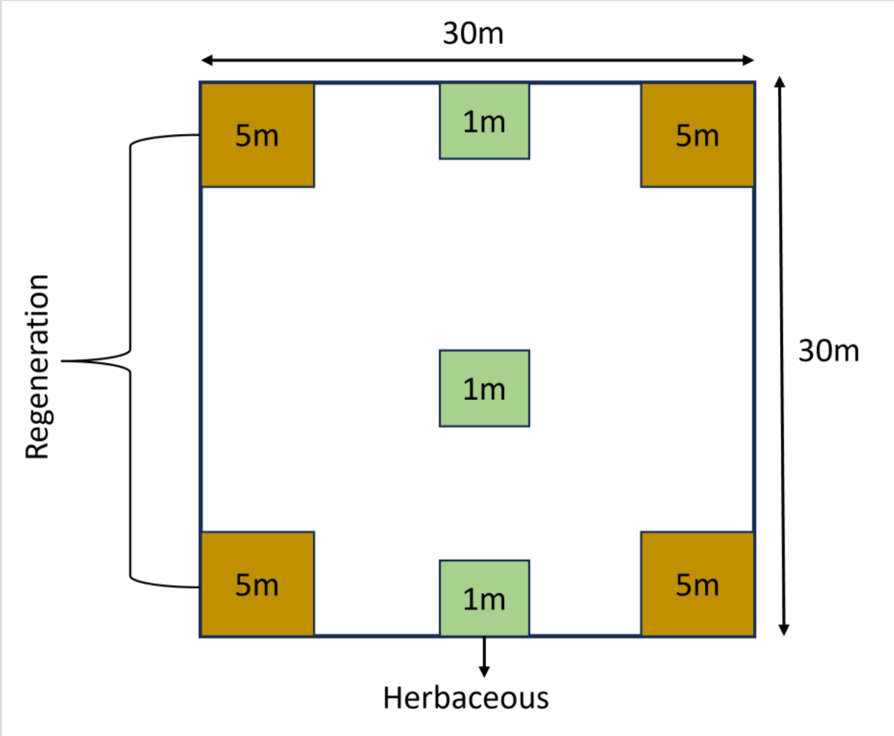

Figure 33: Plots measurement of inventory carried out in the field

Plots were selected to represent areas with different fire histories based on categorising fire risk areas to carry out the phytosociological inventory of the species woody, regeneration, and herbaceous components. A total of 439 plant species were identified.

Data collection was concentrated on woody species composition, species diversity, vegetation structure, fire characteristics and environmental variables. Within each plot, all woody plants with a Diameter at Breast Height (DBH) ≥ 5 cm encountered were recorded. DBH was measured using a tape measure for smaller trees and a clinometer for taller trees, mainly where direct tape measurements were challenging. The DBH was measured 1.3 meters (130 cm) above the ground following standard forestry protocols. A tape measure was wrapped around the trunk at this height, and the circumference recorded was converted into DBH using the formula for calculating circumferences: the species name, DBH, and height for each individual and its abundance-dominance coefficient. Unidentified species were collected and later identified using herbarium specimens at the University of Ghana. Also, all ligneous plants with a DBH ≥ 5cm physical parameters such as height and crow diameter were measured with a focus on frequent burnt life forms to assess the regeneration dynamics. Species richness was recorded as the total number of woody species in each plot, and the Shannon-Wiener diversity index (H') was calculated for each plot. Qualitative ecological characterisation, including edaphic variables (soil texture, structure) as well as topographic attributes (slope, plateau, versant, valley, and bank) and human disturbance factors (fire, farming, cutting, and pasture) (Fousseni et al., 2011). Field observations and visible signs of fire (scorched vegetation, charcoal residues, fire scars on trees, burn tree barks) were also observed, as seen in ***Figure 34***.

Figure 34: Visible signs of ongoing wildfires captured in Busunu showing their effects on vegetation: Source; Field survey 2024.

For the assessment of large-scale vegetation cover changes, MOD13Q1 (MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid) NDVI data from the NASA Earth Observing System Data and Information System (EOSDIS) platform (available at: https://earthexplorer.usgs.gov/), was used. The MOD13Q1 product provides bi-weekly composite images at a spatial resolution of 250 meters. The 250-meter spatial resolution allowed for a detailed analysis of vegetation cover changes at regional and local scales, while the 16-day temporal resolution facilitated tracking of seasonal and interannual variability in vegetation cover between 2000 and 2021. MODIS NDVI data were selected according to cloud covering percentage of less than 10% and data availability in the dry season to reduce cloud effects, vegetation phenology and differences in soil moisture (Wu et al., 2021). Also, thirty (30) GPS ground truth points (UTM Zone 30N, WGS 84 at 3 m level of accuracy) were obtained from sample points of the identified land cover classes (forest (F), shrubby/woody savannah (SWS), Agroforestry/park/field lands (AF), waterbodies (WB), and human settlement (HS) during field visits across the study area. These GPS points were also used to validate the satellite-based vegetation indices.

Hypotheses Testing

Table 15 presents a structured hypothesis test using various statistical approaches to determine the significance of wildfire intensity, frequency, and associated vegetation changes. The independent variables in this analysis primarily include fire intensity and frequency, derived from MODIS remote sensing data. In contrast, the dependent variables focus on key ecological indicators such as species composition, tree cover, species richness, and vegetation changes. The statistical tests applied, including Canonical Correspondence Analysis (CCA), One-Way ANOVA, Shannon-Wiener Diversity Index, and Regression Analysis, allow for a comprehensive assessment of the relationship between wildfire regimes and vegetation structure.

These hypotheses provided insights into how different fire regimes influence species dominance, ecosystem resilience, and vegetation change. The expected outcomes suggest that frequent and high-intensity wildfires drive significant changes, such as species turnover, reduced tree cover, and shrubland expansion, which have long-term implications for savannah ecosystem stability and biodiversity conservation.

Table 15: Hypotheses testing on Wildfire Effects on ecosystem structural diversity and Vegetation

Hypotheses	Statistical Test	Independent Variables	Dependent Variables	Expected Outcome
H_{01}: Different fire regimes (low, moderate, high intensity) do not significantly affect species composition and vegetation structure. **H_{11}:** Different fire regimes significantly influence species composition and vegetation structure.	Canonical Correspondence Analysis (CCA)	Fire intensity (derived from MODIS data).	Vegetation structure, tree density, species composition.	Shifts in dominant species based on fire regimes
H_{02}: Frequent wildfires do not significantly reduce tree cover or alter species richness in fire-prone areas. **H_{12}:** Frequent wildfires reduce tree cover and significantly lower species richness in fire-prone areas.	One-Way ANOVA Shannon-Wiener Diversity Index, IVI	Low, moderate, and high fire frequency plots. Fire Frequency	Tree cover percentage Species Richness	Tree cover declines significantly with increased fire frequency Lower species richness in frequently burned plots
H_{03}: Frequent high-intensity wildfires do not significantly alter vegetation structure in fire-prone areas of the northern savannah zone of Ghana. **H_{13}:** Frequent high-intensity wildfires promote shrubland expansion and decrease forest cover in fire-prone areas of the northern savannah zone of Ghana.	Regression Analysis (Fire intensity vs. NDVI Change)	Fire intensity (measured using MODIS fire data	Vegetation change (measured using NDVI change from Landsat satellite imagery over time	More significant vegetation degradation in high-fire-intensity areas

4.5. DATA PROCESSING AND ANALYSIS

Flora Structure of Yearly Burnt Ecosystems

Following Whittaker (1972), species richness and family spectra were analysed to determine the number of species present in an ecosystem and highlight the distribution of these species across various plant families. All species within the study area were identified and classified into respective families. The dominance of certain species was determined by calculating the number of families per species. Additionally, a comparison was made between burned and non-burned areas to observe changes in species composition as a result of wildfires (Bond & Keeley, 2005). The life form types of the species were also classified based on structural characteristics and adaptation strategies (e.g., trees, shrubs, grasses, herbs). This analysis included the distribution of life forms in frequently burned versus non-burned areas to ascertain how fires may influence certain life forms (Bond & Keeley, 2005).

A plant chorology statement was used to document the origin of species, classifying species as endemic, native, or exotic. This analysis aimed to examine how fire influences the presence and spread of native versus exotic species and how these species' compositions change over time (Preston, 1962;Bond & Keeley, 2005). Further analysis compared the ratio of frequently burned to non-burned species, highlighting fire's impact on species distribution. This involved identifying species predominant in both burned and non-burned areas and calculating the ratio of species abundance (Archibald & Bond, 2004; Bowman et al., 2009).

Species Richness and Evenness

Generalised Linear Mixed Models (GLMMs) were employed to assess the effects of fire frequency and intensity on species richness using the Shannon-Wiener diversity index (Magurran, 2021). The Shannon-Wiener index (H') was calculated as follows:

The value of H' obtained from empirical data usually falls between 1.5 and 3.5 and rarely surpasses 4 (Magurran, 2021). Below is the equation of how this can be achieved;

$$H' = -\sum(P_i \ln P_i)$$

Where: H' = Shannon diversity index, pi = proportion of individuals belonging to species "i", ln = natural logarithm.

Higher values indicate greater species diversity within an area and also suggests that fire disturbances have allowed a broad range of species to coexist, potentially through processes such as niche differentiation and fire adaptation. Lower values indicate lower species diversity and could also suggest that frequent or high-intensity fires select for only a few fire-tolerant species, reducing overall species richness.

To calculate evenness, the Shannon Equitability Index was employed to determine how similar the abundance of different species is in the area under study.

This was achieved by taking the ratio of the observed diversity to the maximum diversity using the equation;

$$E = \frac{H'}{lnS}$$

Where; E= Evenness, H'= Shannon-Weiner diversity index, InS; S = total number of species in the sample.

A high evenness value suggests a more balanced distribution of species, whereas a low evenness value indicates dominance by a few species.

Indicator Species Analysis

This was performed to identify species associated with different fire regimes and assess the impact of wildfire regimes on woody species composition and structural diversity. A regression analysis was conducted to examine the association of Species abundance and fire frequency to determine how fire occurrence influences species distribution.

- Tree height and fire intensity – to assess structural adaptations of trees to varying fire severities.
- DBH (Diameter at Breast Height) and fire recurrence – to evaluate the effect of repeated fires on tree growth dynamics.

Given the potential for non-linear relationships between fire variables and vegetation structure, the Spearman correlation coefficient was applied to measure the strength and direction of these associations. Data was visualised using scatter plots generated using R software (version 4.1.0), utilizing the ggplot2 package for graphical representation. Regression trend lines were fitted to illustrate how different fire regimes influence species structure, providing insights into the resilience and vulnerability of woody species in fire-prone savanna ecosystems.

Importance Value Index (IVI)

The Importance Value Index (IVI) was calculated by combining the relative density and Relative Frequency of Pyrophyte species to assess the ecological significance of each species within the community. IVI with higher values indicated that the species is ecologically present within the study area due to its high density or frequent occurrence. On the other hand, lower IVI values indicate less influential species within the study plot, either due to their low abundance or restricted distribution. The formula below was used to compute IVI;

$$IVI = RF + RD$$

Where RF is relative frequency, it is calculated as the number of unique plots in which that species appears.

$$RF = \frac{Frequency\ of\ Species}{Total\ Number\ of\ Plots}$$

Relative Density is a measure of the abundance of a species in relation to the total number of individuals in the dataset. It is calculated using the formula:

$$RD = \frac{Number\ of\ individuals\ of\ a\ species}{Total\ number\ of\ individuals\ of\ all\ species}$$

Vegetation Change Dynamics- Land Use Change Classification

For the study area, shape files were used to extract data on the various land covers: forest, shrubby/woody savannah, agroforestry parks/fields/fallow land, water bodies, and human settlements for 2000, 2005, 2010, 2015, and 2021. The Semi-Automatic Classification Plugin (SCP) in QGIS was used to classify each pixel accurately before change detection, and the results were then exported to Excel for further analysis (Congedo, 2016). The SCP 'Land Cover Change' algorithm produced the transition matrices that described the changes in different land cover types, thereby pointing out the deforestation rate and how the agricultural lands have been expanding. The SCP "Classification Report" algorithm created Excel reports of the LULC class areas for each period to determine the change rate. The average annual rate of land cover change was calculated using the formula:

$$\frac{Area\ at\ final\ year - Area\ at\ initial\ year}{Area\ at\ initial\ year} \times \frac{1}{number\ of\ years} \times 100$$

This was used to calculate changes in forest cover, shrubby savannah, agroforestry lands, and human settlements.

Preprocessing of MODIS NDVI Image

The original sinusoidal MODIS data projection was reprojected to the WGS 1984 coordinate system, as it is the current standard used by most geographic information systems or GIS datasets. Since MODIS data intrinsically have pixels affected by clouds, cloud masking was developed from the QA layers that come with such data (J. Dwyer & Schmidt, 2006). This ensured that only pixels free of clouds were retained for computation in NDVI. To refine data quality, atmospheric correction techniques, such as the 6S atmospheric correction model, were applied to reduce distortions due to aerosol and water vapour. This step increases the reliability of NDVI values. Later on, data clipping was done to focus on specific study areas, such as the Northern region, Upper West, Upper East, Savannah, and North East region. This type of spatial subsetting reduced the volume of the data and kept the analysis concentrated on the relevant geographic areas. In the case of computing NDVI, the precalculated values are obtained using a formula from the red (visible) and near-infrared (NIR) reflectance bands in the equation below;

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

The NDVI values ranged from -1 to 1, with higher values indicating healthy and dense forest vegetation, while lower values corresponded to sparse vegetation, urban areas, water bodies, and bare land. NDVI values were followed by LULC classification, where vegetation cover was differentiated into various classes based on the NDVI values and other contextual information. These categories included Forest in dark green, Shrubby/Woody Savannah in light green, Agroforestry Parks/Fields/Fallow Land in yellow-green, Water Bodies in blue, and Human Settlements in orange. Generally, areas with forests had a high NDVI due to the high density of vegetation. At the same time, shrubby/woody savannah and agroforestry showed moderate NDVI values due to poor vegetation coverage. Non-vegetated surfaces like water bodies and human settlements did not tend to return high NDVI values.

Testing of the classified images

Images were validated using the accuracy metrics, which included Overall Accuracy (OA), Kappa Statistic (KS), and the Confusion Matrix (CM), to analyse and confirm their statistical accuracy. The statistical classification testing generated confusion matrices for every classified image using the sklearn library (from sci-kit in Python) to create confusion matrices. The overall accuracy (OA) was obtained by comparing the ratio of accurately classified pixels to the number of reference points of the entire image (Kamusoko, 2022). This metric gave a rough estimate of the degree of fit of the classified output data to the reference data and was computed from the following equation below:

$$Overall\ Accuracy = \frac{Total\ Correct\ Classifications}{Total\ Number\ of\ Reference\ Points} \times 100$$

Producer's Accuracy was then calculated using the formular below to determine how well each class in the actual field was classified in the image. It quantified the omission error that arises when a certain land cover type is classified into the wrong class (Kamusoko, 2022).

$$Producer's\ Accuracy = \frac{Correctly\ Classified\ in\ Row}{Total\ in\ Row} \times 100$$

User's Accuracy was computed to measure the likelihood of the pixel being correctly classified to the intended land cover class in the reference data (Kamusoko, 2022;Prasad, 2020). It is a measure of commission error whereby a pixel is either misclassified in an image or computed incorrectly in a matrix. This formular below was used for the accuracy classification;

$$User's\ Accuracy = \frac{Correctly\ Classified\ in\ Column}{Total\ in\ Column} \times 100$$

In addition, the Kappa Coefficient was computed to quantify the degree of agreement between classified data and reference data besides the chance variable. The Kappa coefficient varies from 0 to 1, where values closer to 1 indicate a higher level of compliance between the classification and actual ground truth (S. Prasad, 2020)

$$Kappa = \frac{Po - Pe}{1 - Pe}$$

Where:

Po is the observed accuracy (same as overall accuracy), and *Pe* is the expected accuracy by chance.

4.6. RESULTS

4.6.1. Analysing Species Composition and Diversity (General Plant Diversity)

The floristic inventory reveals 123 species distributed across 102 genera and 38 families in the survey, as seen in ***Figure 35***. The most represented family is Fabaceae, at 23% (***Figure 35***), followed by several families with moderate to low frequencies ranging from 21% to 1%, such as Poaceae, Malvaceae, Anacardiaceae, Sapotaceae, Asteraceae, Rubiaceae, Combretaceae, Meliaceae, and Ebenaceae. The high abundance of Fabaceae in the Savannah ecosystem, as indicated by its numerical representation across sampling sites, can be attributed to several ecological and evolutionary factors, including its unique symbiotic relationship with nitrogen-fixing bacteria (*Rhizobia*) in their root nodules usable by plants, providing them with a competitive advantage in nutrient-poor.

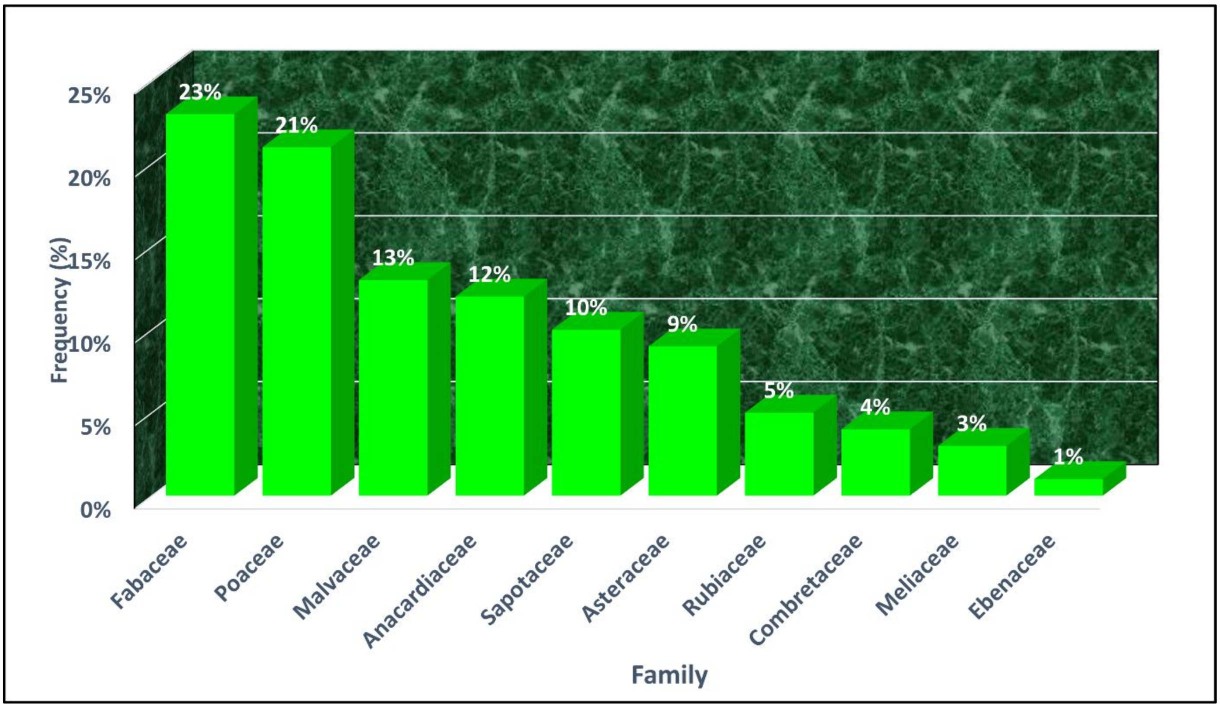

Figure 35: Frequency Distribution of Plant Families in the Study Area: *Source; Field data (2024) / Generated from study data using 'R'.*

Figure 36 shows the relative frequency distribution of the abundant species (herbaceous and ligneous) recorded in the study area. *Vitellaria paradoxa* was the most abundant, making up 14%. At the same time, *Corchorus aestuans*, *Parkia biglobosa*, and *Sida acuta* each comprised 11% of the overall species composition, indicating relative importance in dominating the species makeup. *Anogeissus leiocarpus* and *Diospyros mespiliformis* each contribute 10% of the species. This indicates a high representation of the vegetation structure. *Eleusine indica* represents 9%, *Blighia sapida* and *Tridax procumbens* have a frequency of 8%, showing that these species are strongly present. Similarly, *Adansonia digitata*, with 7% of the total species, makes it one of the less frequent in the whole study area.

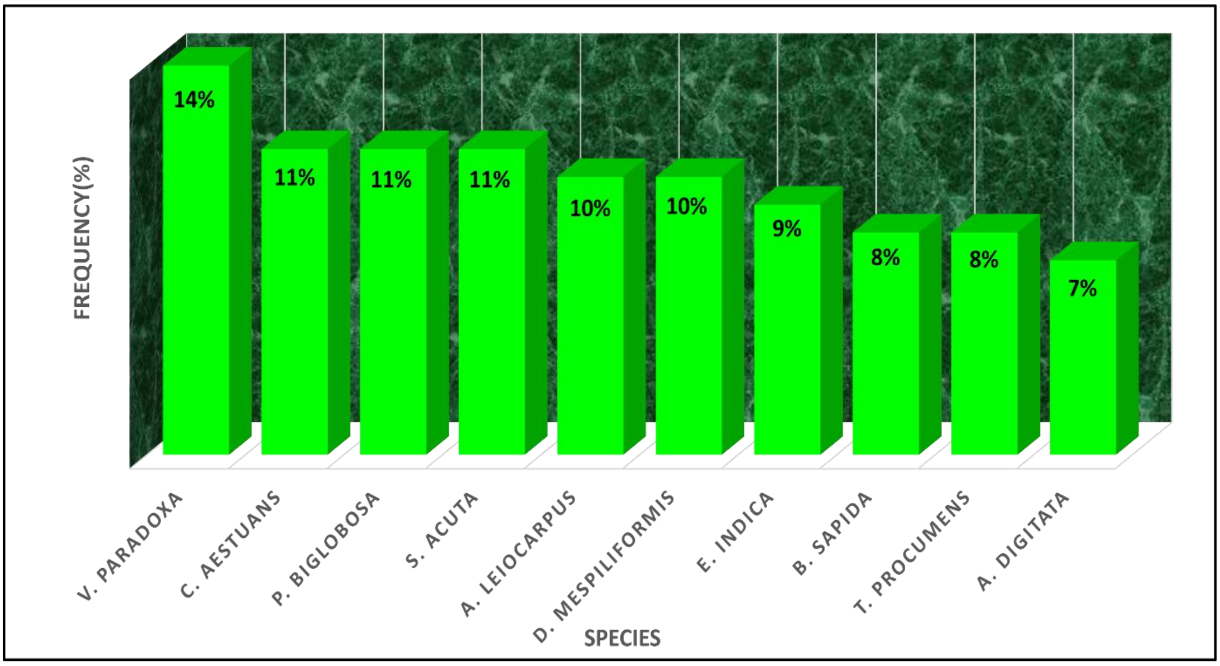

Figure 36: Relative Frequency Distribution of Abundant Species in the Savannah: Source; Field data (2024) / Generated from study data using 'R'.

4.6.2. Relative Frequency Distribution of Pyrophyte Species in the Savannah

Pyrophyte species are plants adapted to survive and even thrive in fire-prone environments. (***Figure 37***) below shows the relative frequency of the pyrophyte species identified within the entire study plots and dominated by *Vitellaria paradoxa*, with a relative frequency of 18%, followed by *Parkia biglobosa*, *Anogeissus leiocarpa*, *Diospyros mespiliformis*, *Adansonia digitata*, *Balanites aegyptiaca*, *Lannea acida*, *Azadirachta indica*, *Afzelia africana*, and *Acacia dudgeoni*, with representative frequencies ranging from 14% to 5%. Pyrophyte species have developed specific traits that allow them to withstand frequent fires, a common disturbance in Savannah ecosystems.

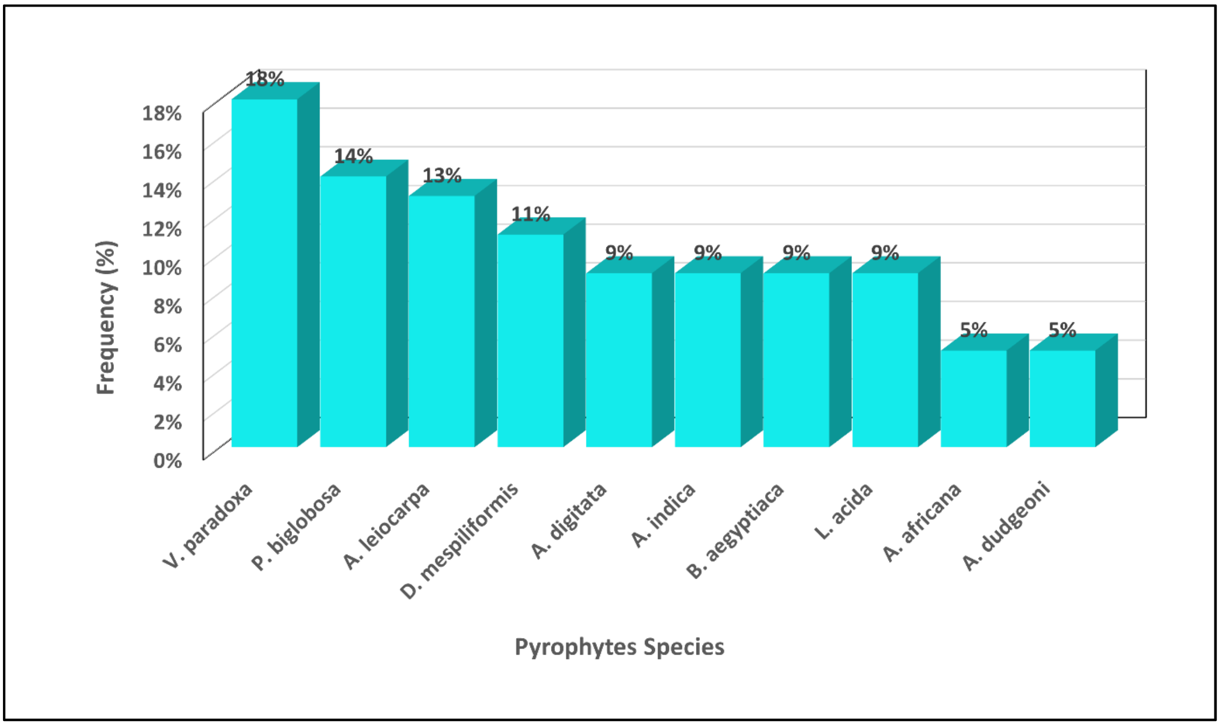

Figure 37: Frequency distribution of pyrophytes species in the savannah: Source; Field data (2024) / Generated from study data using 'Microsoft Excel

4.6.3. Life Form Spectra in Burned and Non-Burned Areas

Figure 38 below shows the frequency distribution of biological types in two distinct ecological categories: SP BRUT and SP POND. SP BRUT refers to species from harsher environments, potentially influenced by frequent disturbances like fire. SP POND refers to species from water-rich environments such as ponds, wetlands, or other aquatic habitats.

The raw spectrum data represents the proportional occurrence of biologic types in the total recorded plant species within the study area. It provides insight into the dominant life forms and their ecological roles. By categorizing species based on their biologic types: micro-phanerophytes **(mp),** therophytes **(Th),** meso-phanerophytes **(m_P),** chamaephytes **(Ch)**, Nano-phanerophytes(**np),** Hydrophytes **(H)**, Microphanerophyte Lianas, **(Lmp)**, Parasites **(Par)**, Geophytes **(Ge)**

The raw spectrum data highlights the dominance of ***micro-phanerophytes***, which account for 35.91% of the total spectrum, with an average coverage of 33.27%. These species, including *Acacia dudgeon*, *Acacia nilotica*, *Balanites aegyptiaca*, *Burkea africana*, and *Vitellaria paradoxa*, are small trees and shrubs ranging from 2 to 8 meters tall. Their prevalence, particularly in SP BRUT, suggests their resilience in disturbed environments, as they possess fire-adaptive traits such as thick bark, deep root systems, and the ability to resprout after fire events. The predominance of this group underscores its crucial role in maintaining the structural composition of the savanna ecosystem. ***Therophytes*** represent 21.94% of the raw spectrum, with an average coverage of 26.59%, making them the second most dominant biologic type. These species, including *Amaranthus hybridus*, *Aspilia africana*, and *Corchorus olitorius*, are short-lived annuals that complete their life cycle within a single season. Their high representation, particularly in SP POND, suggests their ability to thrive in areas with periodic moisture availability. The dominance of therophytes also indicates a high degree of environmental fluctuation, as these species persist through seed dormancy and germinate rapidly when favourable conditions return. ***Meso-phanerophytes***, comprising medium-sized trees and shrubs between 8 and 30 meters tall, exhibit a moderate presence in the raw spectrum. These include *Afzelia africana, Albizia coriaria, Daniella Oliveri, Detarium Senegalese,* and *Terminalia avicennioides*, which contribute to the canopy structure and influence microclimatic conditions. However, their lower proportion compared to micro-phanerophytes suggests that they may be more susceptible to fire or have longer regeneration cycles, limiting their dominance in frequently disturbed environments.

Other biologic types, including ***nano-phanerophytes***, ***chamaephytes***, and ***hydrophytes***, contribute to the diversity of the savannah ecosystem but at lower frequencies. Nano-phanerophytes, small woody perennials under 2 meters in height, include species such as *Asystasia gangetica*, *Cephalanthus occidentalis*, and *Sida acuta*. Chamaephytes, which grow close to the ground and include *Aneilema sp., Commelina sp.,* and *Oxalis stricta*, are often adapted to fire due to their low growth habit and ability to regenerate from below-ground stems. Hydrophytes, which include grasses and herbaceous perennials such as *Vetiveria nigritana*, play a role in maintaining the ground cover and contributing to fire resilience in grassy savannahs. ***Geophytes*** and ***parasite*** species are the least represented biologic types. Geophytes, which survive disturbances through underground storage organs, appear in low proportions, with *Cyperus strigosus* being a rare example. Similarly, parasitic species, such as *Striga hermonthica*, are minimally present, indicating that these biologic types may have a limited ecological role within the study area.

The overall composition of the raw spectrum reflects a fire-adapted savannah ecosystem, where micro-phanerophytes and therophytes dominate, shaping vegetation structure and recovery dynamics. The prominence of small trees and annual species suggests a system characterised by frequent disturbances, where species with resprouting abilities and rapid regeneration strategies thrive. The moderate presence of meso-phanerophytes further suggests the influence of land-use pressures or environmental constraints on larger tree species. Chamaephytes, hydrophytes, and nano-phanerophytes contribute to the diversity of understory vegetation, reinforcing their ecological significance in maintaining savannah stability. The low representation of geophytes and parasites suggests that these biologic types play a minor role in shaping the vegetation dynamics of the study area.

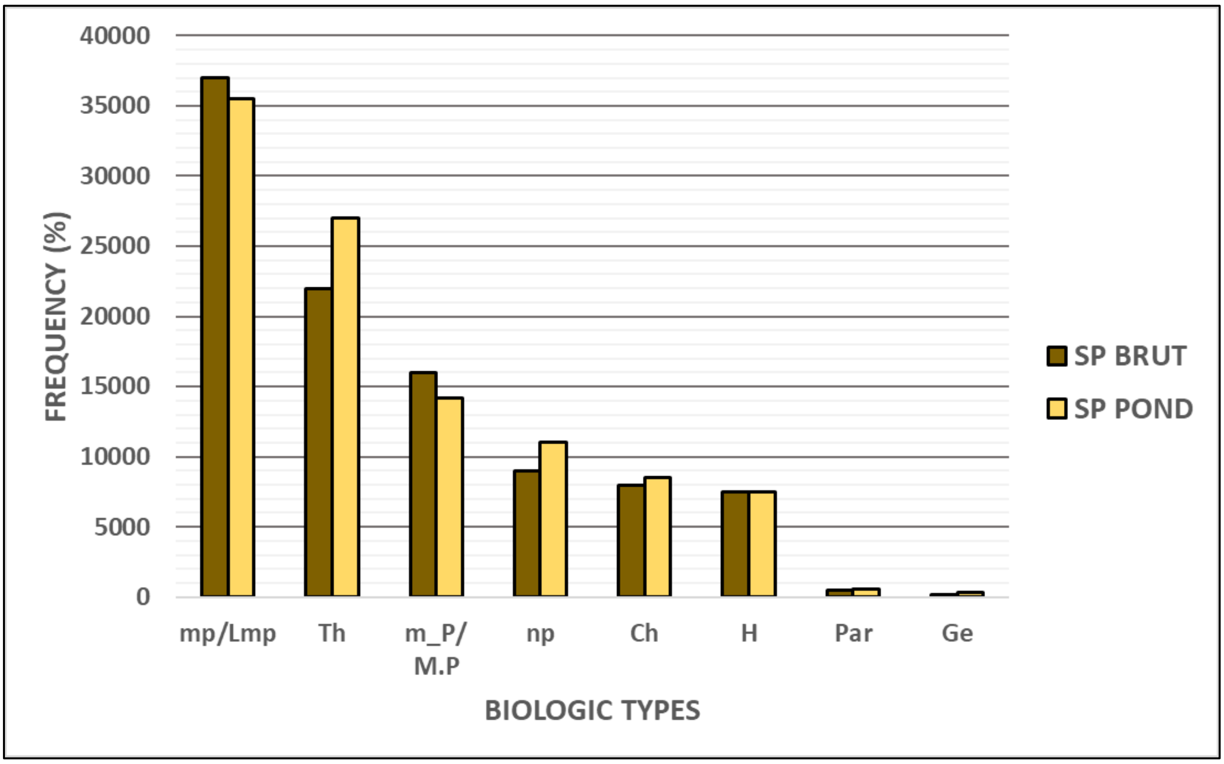

Figure 38: Distribution of plant life form spectra; Source: (Field Survey,2024)

Phytogeographic Types

(***Figure 39***) represents the frequency distribution of phytogeographic types within the two marked ecological categories, SP BRUT and SP POND. It reflects how different species of various geographical origins are distributed between these two habitat types. The Guineo-Congolese / Sudano-Zambezian (GC-SZ) species recorded the highest frequency in SP BRUT and SP POND, about 43% and approximately 42%, respectively. This suggests that the species in this transitional region between tropical and savanna ecosystems dominated both environments. Sudano-Zambezian (SZ) species are the second most frequent, forming about 27% of SP BRUT and 23% of SP POND. These species are generally well adapted to drier, more savanna-like conditions, which could be a reason for their higher presence in both ecological categories. Guineo-Congolese (GC) species are prevalently represented in SP BRUT and SP POND by approximately 10%. These plant communities also include species characteristic of moist, tropical forests but are much less dominant here. Introduced species (i) represent about 8% of SP BRUT and 5% of SP POND, which means they have moderate representation. This may show that human activities could have introduced species that may adapt to both environments. Atlantic (AT) and Afro-American (AA) have lower frequencies, each contributing about 6% and 5%, respectively, from SP BRUT, slightly lower in SP POND. South Guinean (SG), Panafrican (Pan), and Cosmopolitan (Cosmc) species, whose representation is relatively low, standing between 3% and 5% in both SP BRUT and SP POND. The Paleotropical (Pal) and Austral-African (AN) species are the least represented, with less than 2% of the species in both categories. These further indicate that both SP BRUT and SP POND are dominated by GC-SZ and SZ species, suggesting that species from transition zones between tropical and savanna zones are comparatively better adapted to disturbed and moist environments. The occurrence of GC species in both environments shows that even tropical species may persist, though they are less common. The overall moderate representation of introduced species indicates some human impact across both environments. However, South Guinean, Panafrican, Cosmopolitan, Paleotropical, and Austral-African species have lower frequencies, reflecting their more specialised or limited ecological ranges.

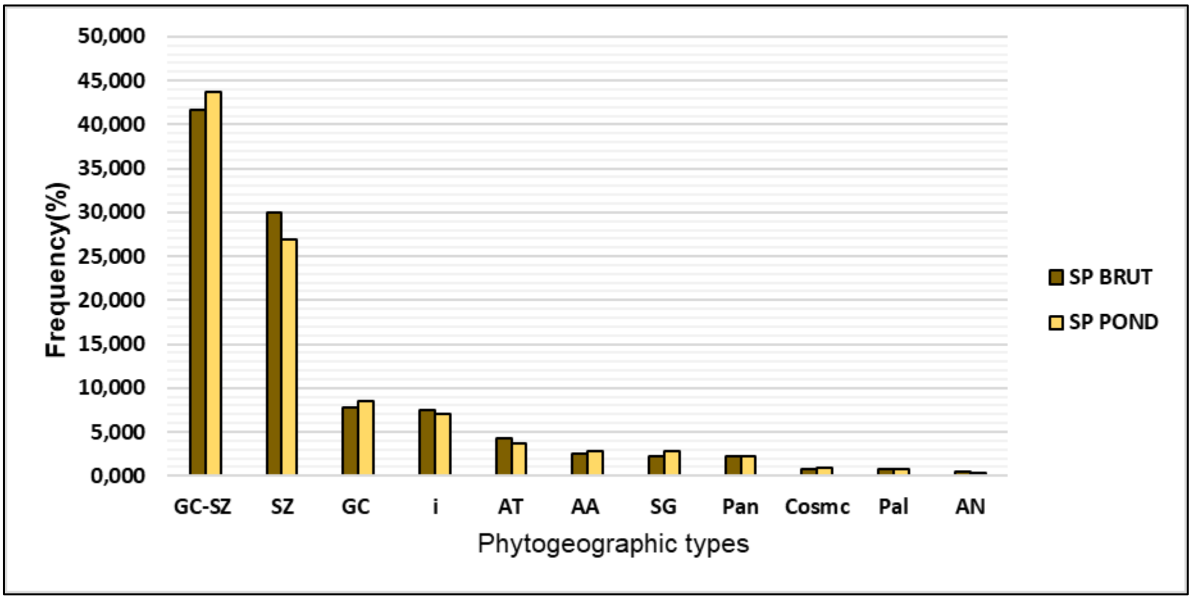

Figure 39: Distribution of Plant Phytogeographic spectra; Source: Field data,2024

Importance Value Index (IVI) of Pyrophytes Species

The Importance Value Index (IVI) was used to assess the ecological significance of the different abundant species in the study area (***Table 16 and Figure 40***). The analysis shows that *Vitellaria* *paradoxa* recorded the highest IVI (13.59), suggesting it is the most ecologically significant species in abundance, distribution, and dominance. This species is well-represented across plots and contributes significantly to vegetation structure and ecosystem stability. Parkia biglobosa followed with an IVI of 11.35, reflecting its strong presence and ecological importance in the savanna landscape. Anogeissus leiocarpus (IVI = 10.79) is also ranked among the dominant species, crucial in habitat stability and soil conservation. *Diospyros mespiliformis* (9.67) and Adansonia digitata (8.56) exhibit moderate ecological significance, with relatively high densities and widespread occurrence. *Azadirachta indica*, *Balanites aegyptiaca*, and *Lannea acida* also recorded IVI values of 8.56, indicating their adaptation to environmental conditions and role in maintaining ecological balance. *Acacia dudgeoni* (6.32) and *Afzelia africana* (6.32) were notable species, showing moderate dominance within the study area. Some species exhibited lower IVI values, indicating lesser dominance and possible vulnerability. *Terminalia avicennioides* (5.15) and *Burkea africana* (5.15) had relatively lower densities and frequencies, suggesting they may be less adapted to disturbances or face competitive exclusion from more dominant species. Other species, such as *Sterculia setigera*, *Daniellia oliveri*, and *Tamarindus indica*, had the lowest IVI values (below 3), indicating their rarity or limited distribution within the study area. The high-IVI species, including *Vitellaria paradoxa* and *Parkia biglobosa*, are keystone species contributing to ecological stability, carbon sequestration, and biodiversity support. Their conservation is essential to maintaining ecosystem functions and local livelihoods. Moderately ranked species like *Anogeissus leiocarpa* and Diospyros mespiliformis contribute to forest succession and regeneration, whereas species with lower IVI values may require conservation attention to prevent population declines.

Table 16: Frequency, relative frequency, Density, relative density and IVI of pyrophyte species

Species	Frequency	Relative Frequency	Density	Relative Density	I VI
Acacia dudgeon	3	3.53	5	2.79	6.32
Acacia gourmaensis	3	3.53	4	2.23	5.76
Acacia nilotica	3	3.53	3	1.68	5.21
Acacia seyal	2	2.35	3	1.68	4.03
Adansonia digitata	3	3.53	9	5.03	8.56
Afzelia Africana	3	3.53	5	2.79	6.32
Anogeissus leiocarpus	3	3.53	13	7.26	10.79
Azadirachta indica	3	3.53	9	5.03	8.56
Balanites aegyptiaca	3	3.53	9	5.03	8.56
Bombax costatum	2	2.35	2	1.12	3.47
Burkea africana	2	2.35	5	2.79	5.15
Combretum collinum	2	2.35	3	1.68	4.03
Combretum glutinosum	2	2.35	2	1.12	3.47
Combretum molle	2	2.35	2	1.12	3.47
Daniellia oliveri	1	1.18	1	0.56	1.74
Detarium microcarpum	1	1.18	2	1.12	2.29
Detarium senegalense	1	1.18	2	1.12	2.29
Diospyros mespiliformis	3	3.53	11	6.15	9.67
Diospyros virginiana	2	2.35	2	1.12	3.47
Entada Africana	2	2.35	2	1.12	3.47
Gardenia ternifolia	2	2.35	4	2.23	4.59
Hexalobus monopetalus	1	1.18	1	0.56	1.74
Isoberlinia doka	2	2.35	3	1.68	4.03
Isoberlinia tomentosa	2	2.35	2	1.12	3.47
Lannea acida	3	3.53	9	5.03	8.56
Lannea Barteri	2	2.35	2	1.12	3.47
Lannea microcarpa	2	2.35	4	2.23	4.59
Nauclea Latifolia	3	3.53	4	2.23	5.76
Parkia biglobosa	3	3.53	14	7.82	11.35
Piliostigma reticulatum	2	2.35	2	1.12	3.47
Piliostigma thonningii	2	2.35	2	1.12	3.47
Pterocarpus erinaceus	2	2.35	2	1.12	3.47
Sterculia setigera	1	1.18	1	0.56	1.74
Sterculia tragacantha	1	1.18	2	1.12	2.29
Tamarindus indica	1	1.18	2	1.12	2.29
Tectona grandis	1	1.18	2	1.12	2.29
Terminalia albida	1	1.18	1	0.56	1.74
Terminalia avicennioides	2	2.35	5	2.79	5.15
Terminalia glaucescens	1	1.18	1	0.56	1.74
Vitellaria paradoxa	3	3.53	18	10.06	13.59
Vitex doniana Sweet	2	2.35	4	2.23	4.59
Total	**85**	**100.00**	**179**	**100.00**	**200.00**

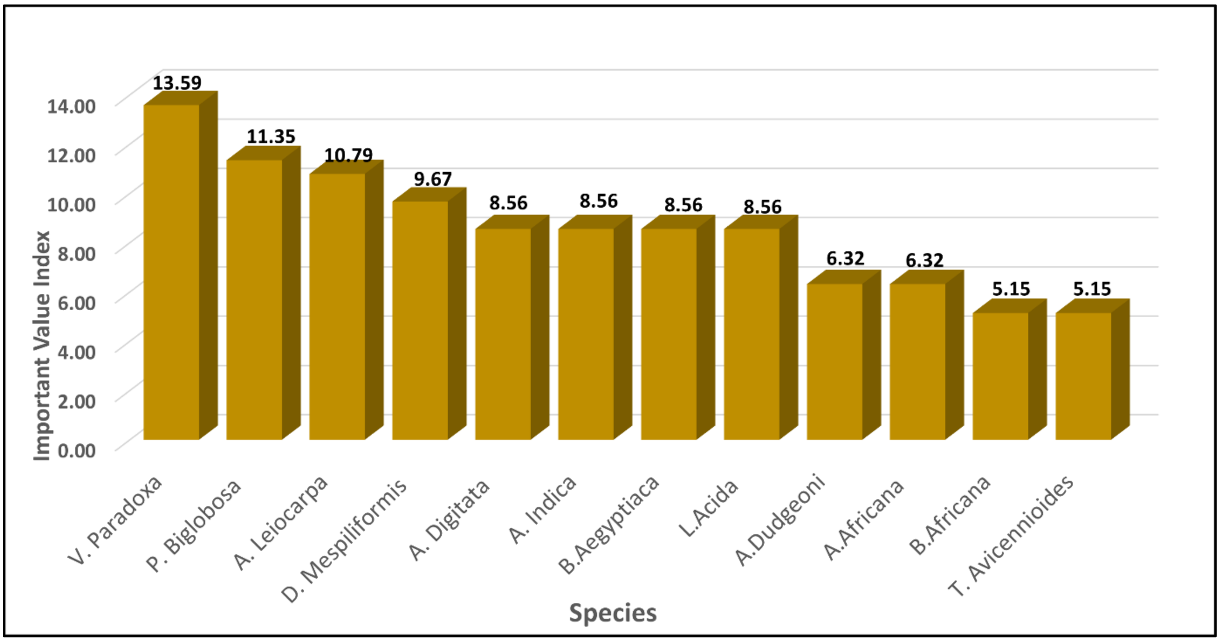

Figure 40: Importance Value Index (IVI) of abundant pyrophytes species in the study area, illustrating the most and least ecologically significant species: Source; (Field Survey, 2024), generated from Microsoft Excel)

4.6.4. Species Accumulation and Estimated Richness in the Study Area

Species Richness Curve

The species richness curve in ***Figure 41*** below represents how species richness increases with the number of sites sampled. The blue line shows the increasing number of species identified as more sites are sampled. Analysis of this curve shows that the number of species strongly correlates with the number of surveys. The curve steeply increases at the beginning, suggesting that many new species are found in the initial sites. Surveys conducted in 5 plots recorded 20 plant species; 45 species were inventoried at 10 plots. As the number of surveys increases in each plot, new species continue to appear, allowing the recording of approximately 121 species in 30 surveys (Plots). However, as the number of sites increases, the curve gradually flattens, meaning fewer new species are being discovered, and the total species richness is approaching a plateau, meaning the majority of species in the area have likely been recorded. However, the richness estimators suggested that additional surveys may still reveal 20–30 more species, particularly rare ones, if the number of surveys exceeds 30.

Comparing it with species richness estimators by applying extrapolation using Chao and Jackknife 2 methods, the species richness is estimated to be 150 at 160 species. According to Jackknife 1 and Bootstrap extrapolation methods, the estimated richness is 155 and 149 species, respectively.

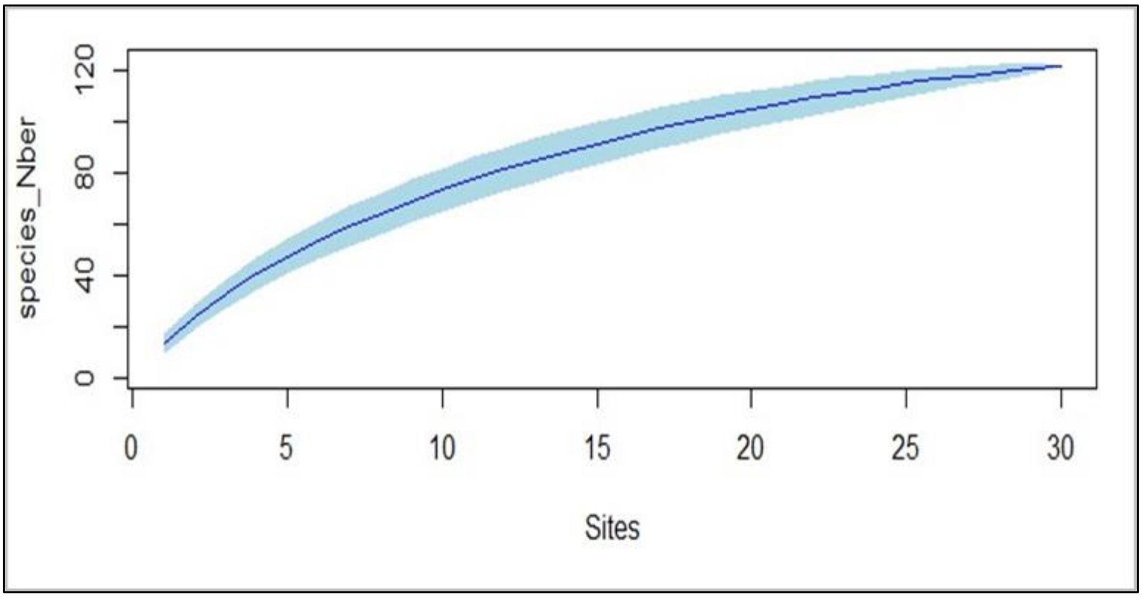

Figure 41: Species Richness curve: ***Field data (2024) / Generated from study data using 'R'.***

This multi-panel graph displays the performance of five species richness estimators (S, Chao, Jackknife 1; Jackknife 2, and Bootstrap) as a function of sample size in ***Figure 42*** below. Each panel represents a different estimator, with the x-axis showing the sample size and the y-axis indicating the estimated species richness. The blue line represents the mean estimate, while the yellow lines likely represent confidence intervals or alternative scenarios. This visualization compares how each estimator performs and converges as the sample size increases. The first plot, 'S,' shows the number of species recorded as sampling progresses. It increases with sample size but approaches a plateau. The 'Chao' estimates a higher richness than observed, indicating potential undetected rare species. 'Jackknife 1 & 2', on the other hand, provide progressively higher richness estimates, with Jackknife 2 predicting more unseen species than Jackknife 1. The 'Bootstrap' provides a smoother estimate, generally lower than Jackknife 2 but higher than observed richness, suggesting that sampling is close to complete but may still miss some rare species. All estimators predict higher species richness than observed, implying that additional species might be found with more sampling. However, Chao and Jackknife 2 estimate the highest richness, meaning rare species are likely underrepresented in the current dataset.

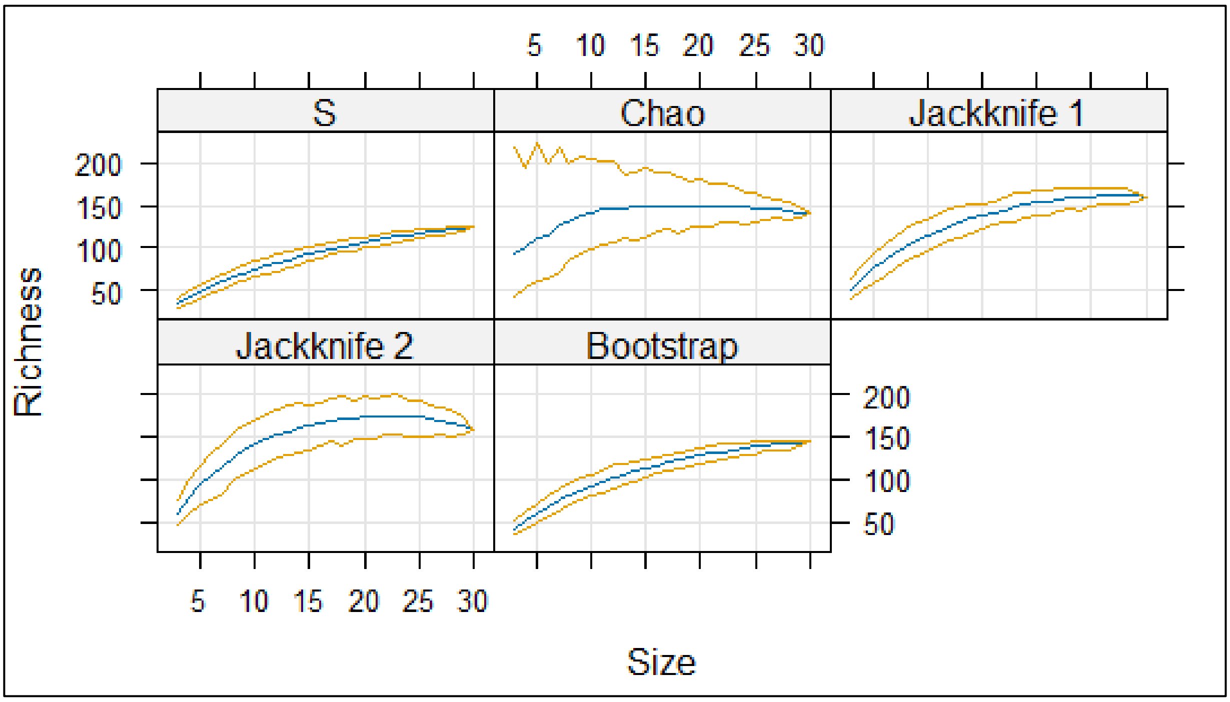

Figure 42: Cumulative Species Richness Estimators Across Different Sample Sizes (Chao/Jacknife/Bootstrap Extrapolation: Field data (2024) / Generated from study data using 'R'.

4.6.5. Typology of Plant Communities Across Fire and Human Disturbance Gradients

It is observed in ***Figure 43*** that the coordination of surveys by Detrended Correspondence Analysis (DCA) shows that plant communities are distributed along the gradients of fire intensity and human-generated disturbances. DCA identifies three significant groups based on the effects of fire and anthropogenic factors like deforestation. The outcome of such analysis provides a visual representation of how environmental variables such as fire frequency and human activities shape plant community composition. Communities in often-burned landscapes may differ significantly from those in seldom-burned ones, as the former groups have adapted to fire-prone environments where the latter are more sensitive. DCA further deconstructs how human activities, such as land use changes, interact with fire regimes to yield such communities, thereby underlining disturbance as an organising force of plant ecosystems. The distribution of the sites along Axis 1 represents a gradient of increasing fire effects associated with long-term deforestation processes. At the same time, Axis 2 indicates an increasing gradient of human disturbances from hunting and farming to charcoal production. These sites fall into three distinct groups:

Group 1 (G1): Open forests, representing 10% of the surveyed plots, consist of 29 species from 28 genera and 15 families. They are mainly threatened by hunting.

Group 2 (G2): Shrubby/tree savannahs with dry forests represented 76% of the surveyed plots. This group includes 104 species from 85 genera and 34 families. Farming and charcoal production are the major threats within this group.

Group 3 (G3): Wooded or tree savannahs comprised 13% of the plots surveyed and included 44 species from 42 genera and 17 families. Hunting and tree-cutting were the main threats to this group.

Each of these groups has various types of human activities. G1 consists of open forests disturbed by hunting, while G2 comprises mosaic savannahs/dry forests disturbed by farming and charcoal production. Hunting and felling of trees are considered significant disturbances for G3, comprising wooded/tree savannahs. The left-to-right gradient is for the increase in the fire-induced effects of deforestation, while the bottom-to-top gradient reflects increased human disturbances. These clusters show how different areas or communities represent variations in impact related to proximity to these processes.

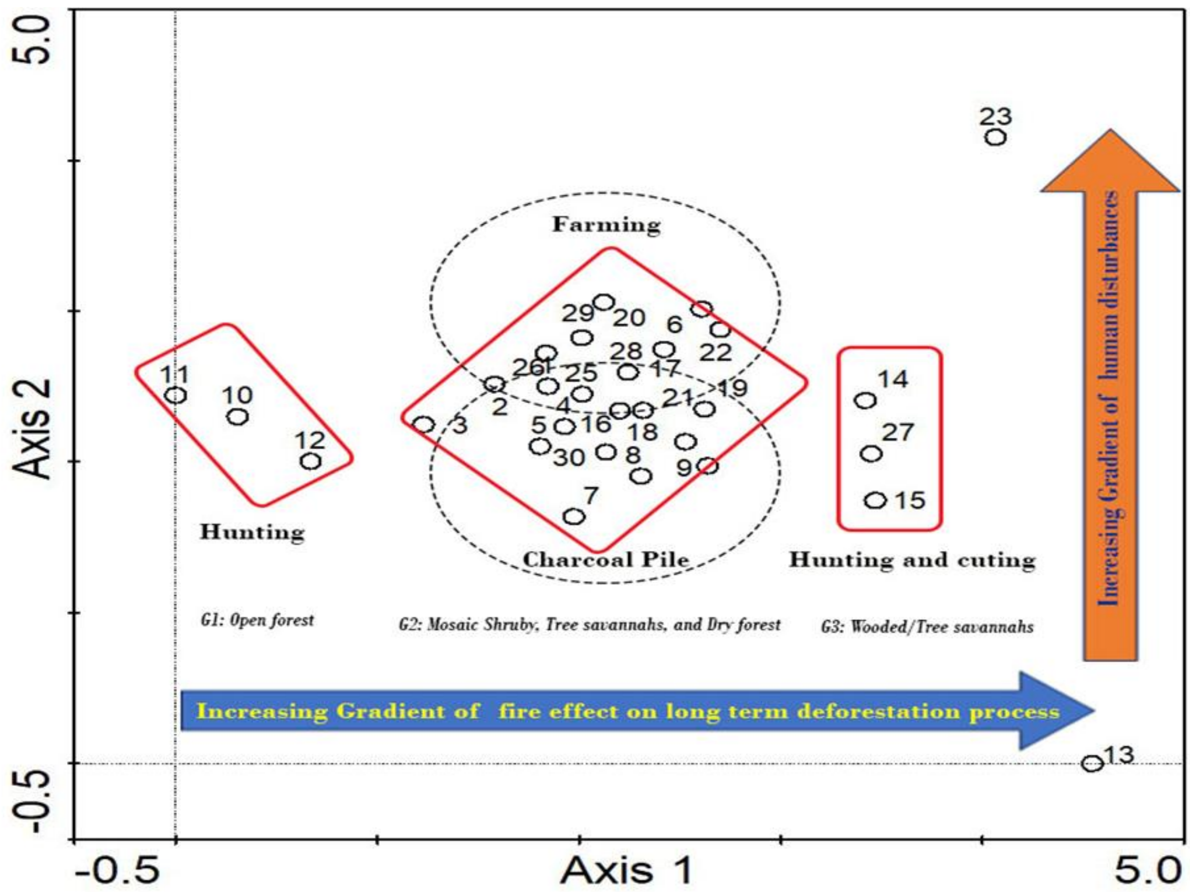

Figure 43: Distribution of Human Activities and Vegetation Types Along Environmental Gradients (Detrended correspondence analysis of 30 plots x 123 plant species): Source; Field data (2024) / Generated from study data using 'R'.

Biological and Ecological Traits Explaining the Occurrence of Fire Across Plant Community

The Canonical Correspondence Analysis (CCA) displayed in (***Figure 44***) illustrates the relationship between environmental variables and species composition across different survey plots. Axis 1 represents a gradient that reflects species and community responses to factors such as vegetation structure, soil type, and the density of dead trees, which dominate the positive side of this axis. On the negative side, human activities and elevation appear as strong drivers of species composition. Axis 2 shows a similar gradient, with vegetation structure and rivers being influential in the positive direction, while human activities and elevation influence species composition in the negative direction. The length and direction of the red arrows indicate the relative importance of each environmental variable in structuring species composition. Vegetation structure is a dominant factor, influencing species distribution positively along both axes. This suggests that human disturbances impact areas with more complex vegetation. Soil type also aligns strongly with the positive side of Axis 1, implying that species in these plots are likely influenced by specific soil conditions favourable for plant growth. The density of dead trees is also strongly correlated with vegetation structure, potentially indicating areas undergoing successional changes or stress.

Human activities are prominent on the negative side of Axis 1, suggesting that species compositions in plots positioned along this axis are more disturbed by anthropogenic factors, such as cutting or farming. Elevation similarly aligns with human activities, likely reflecting the impacts of land use in higher-elevation areas. Rivers influence both axes, particularly in the central portion of the ordination space, indicating that proximity to water bodies affects species composition across multiple plots. Results from CCA also indicated distinct species clustering along fire intensity gradients, with fire-tolerant species dominating frequently burned areas ($F = X$, $p < 0.05$). This led to the rejection of $\mathbf{H_{05}}$ and confirmation of $\mathbf{H_{15}}$, suggesting that increased fire exposure alters vegetation structure by favouring fire-adapted species.

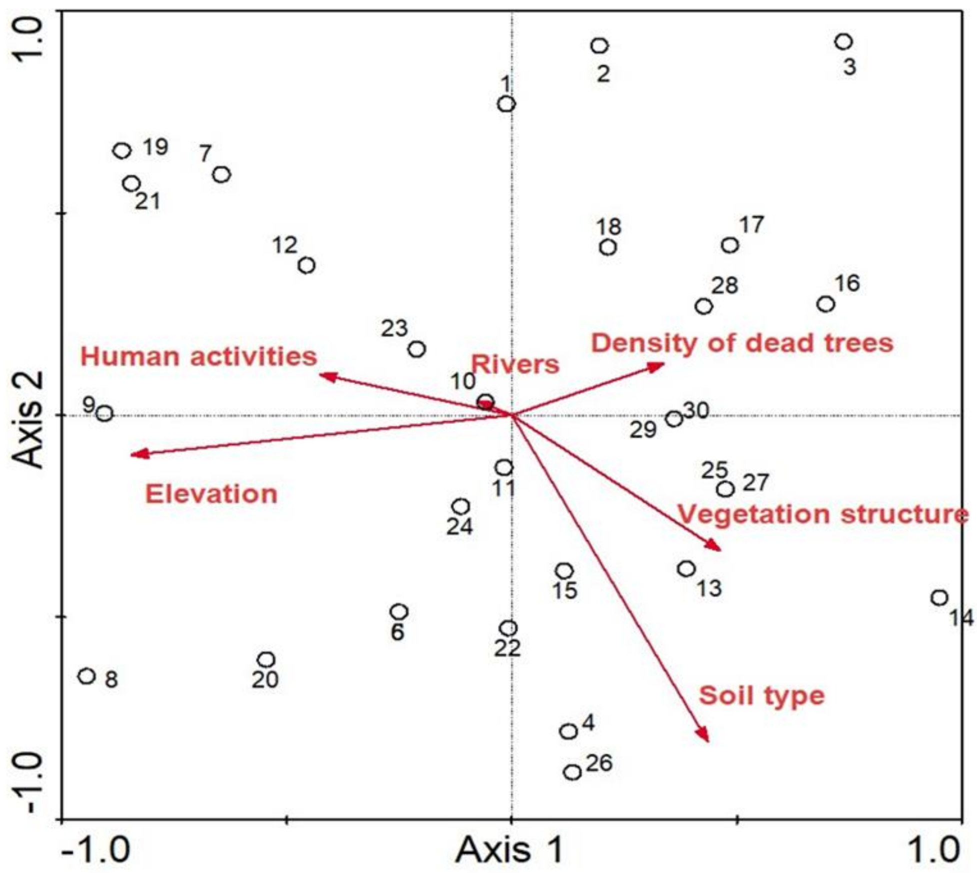

Figure 44: Canonical analysis on the distribution of Human Activities and Vegetation Types Along Environmental Gradients in 30 plots: Source; Field data (2024) / Generated from study data using 'R'

Life Form and Chorology Spectra in Plant Community G1 (Open Forest)

The results presented in ***plate 7 (Figure 45)*** highlight the distribution of biologic and phytogeographic types for SP Brut and SP Pond in plant group 1 open forest. In the biologic types category, Th (therophytes), with a raw spectrum of 25% and an average coverage of 30,10%, exhibits the highest frequency for both SP Brut and SP Pond, suggesting a dominance of annual species that complete their life cycle quickly. Microphanerophytes (mp), with a raw spectrum of 25% and an average coverage of 22.29%, and nanophanerophytes (np), with a 15.90% raw spectrum and 15.08 % average cover, also show significant representation, indicating that small woody plants and shrubs contribute substantially to the vegetation structure in the studied ecosystem. The combined M.P & m_P category, representing mesophanerophytes and microphanerophytes, with 13.63% raw spectrum and 16.67% average coverage, follows closely in frequency, showing a balanced representation of these life forms in both sample categories. Hydrophytes (H) demonstrate a moderate presence, with 13.63% raw spectrum and 11.17% average coverage, and comprise a significant portion of the biological diversity, particularly in SP Pond, which has higher frequencies for these types than SP Brut. Chamaephytes (Ch) and geophytes (Ge) appear in lower frequencies, suggesting their relative rarity in the ecosystem under study.In the phytogeographic types category in ***plate 7 (Figure 46),*** Guineo-Congolese/Sudao-Zambezian (GC-SZ) with 50% raw spectrum and 48.02% average coverage dominate in both SP Brut and SP Pond, indicating the strong influence of these biogeographical regions on species composition.

This dominance suggests species adapted to the Guineo-Congolese and Sudano-Zambezian regions thrive in the ecosystem, likely due to favourable climatic and edaphic conditions. Sudano-Zambezian (SZ) species also show a significant presence, with a raw spectrum of 27% and 26.81% average coverage, with higher frequencies in SP Pond compared to SP, further supporting the importance of this biogeographic transition zone in structuring the vegetation. Guineo-Congolese (GC) species with 11.36% of the raw spectrum and 13.96% of the average coverage are present but in relatively lower frequencies compared to GC-SZ and SZ, but with slightly higher values in SP Brut, indicating a diminishing influence of the Guineo-Congolese floristic region as one move towards drier savanna landscapes. Other phytogeographic types such as Palaeotropical (Pal), Pantropical (Pan), Afro-Tropical (AT), and introduced species (i) show much lower frequencies, implying that their contribution to the overall species composition is relatively minor.

The observed patterns in biologic and phytogeographic types highlight the ecological structure and environmental filtering processes shaping species distribution in the savanna ecosystem. The predominance of therophytes and microphanerophytes suggests an adaptation to seasonal disturbances such as fire and drought, which are characteristic of savannah landscapes. Similarly, the high presence of Guineo-Congolese/Sudano-Zambezian species reflects a floristic transition influenced by humid and dry tropical conditions. These findings provide insights into the resilience of different plant groups in response to environmental stressors, particularly in fire-prone and semi-arid ecosystems.

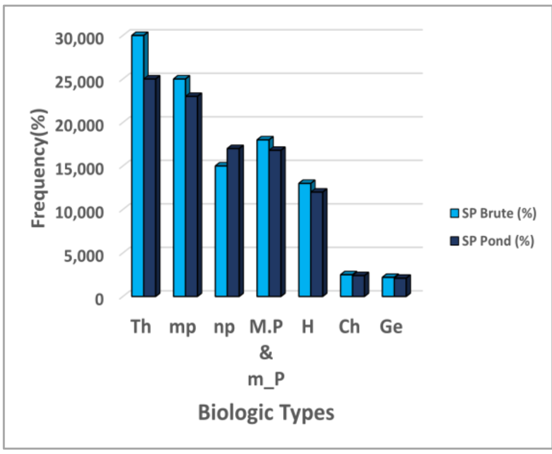

Figure 45: Biologic Types in Plant Community 1

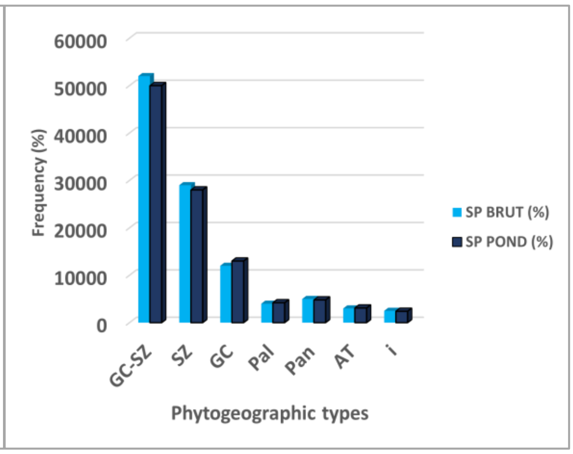

Figure 46: Phytogeographic Types in Plant Community 1

Plate 7: Life form and chorology spectra of species Biologic and Phytogeographic types among plant community in G1: ***Source; (Field survey, 2024)***

Life Form and Chorology Spectra in Plant Community G2 Mosaic, Dry Forest, Tree, and Shrubby Savannah

The biologic and phytogeographic types analysis in ***plate 8 (Figure 47)*** highlights distinct species composition and distribution patterns in Group ***G2 (mosaic, dry forest, tree, and shrubby Savannah)***. The biologic types reveal the dominance of microphanerophytes (mp) and lianas (Lmp), which comprised 35.40% of the raw spectrum with an average coverage of 34.50%. This was followed by therophytes (Th), which comprised 22.50% of the raw spectrum and an average coverage of 27.40%, suggesting an adaptation to disturbance-driven environments. The high representation of microphanerophytes and lianas indicates a structurally diverse vegetation composition, likely influenced by fire regimes and human disturbances. Therophytes are well represented and are short-lived annuals, emphasising the role of disturbance and seasonal environmental variability in shaping species composition. Mesophanerophytes and microphanerophytes (m_P & M.P) represent a substantial share, with 16% of the raw spectrum and 13.35% of coverage, reinforcing the importance of small and medium-sized woody plants in this ecosystem. Other biologic types such as nanophanerophytes (np), chamaephytes (Ch), hemicryptophytes (H), geophytes (Ge), and parasites (Par) appear in lower proportions, indicating their limited distribution in this plant community.

The phytogeographic composition of the plant community ***plate 8 (Figure 48)*** shows a predominant influence of Guineo-Congolese/Sudano-Zambezian (GC-SZ) species, which account for the highest frequency in both SP BRUT and SP POND. They are represented by 28.67% and 25.15% in the raw and weighted spectrum, respectively. This suggests a strong biogeographic transition between the humid Guineo-Congolese and the drier Sudano-Zambezian regions, which shape species composition in this ecosystem. Sudano-Zambezian (SZ) species also contribute significantly to the community structure, reinforcing the dominance of species adapted to seasonally dry and fire-prone environments. Other phytogeographic types, including Guineo-Congolese (GC), Afro-Tropical (AT), and African-Asiatic (AA) species, are present but in lower proportions, indicating a secondary influence from more humid or broader biogeographic regions. The presence of introduced species (i) in group G2 and the study areas further underlines the role of fire and human activities on the composition of such ecosystems. Sudano-Guinean (SG), Cosmopolitan (Cosmc), Pantropical (Pan), Palaeotropical (Pal), and Atlantic (Atl) species are present in much smaller frequencies, suggesting that their contribution to the overall species diversity is relatively minor.

The comparison of SP BRUT and SP POND in biologic and phytogeographic types illustrates the difference between raw species frequency and weighted ecological representation. In most categories, SP POND values are slightly higher for abundant species, reflecting their relative abundance and ecological significance. This weighting provides a more refined perspective on species distribution by emphasising dominant and structurally essential species in the plant community. The overall results highlight a vegetation structure shaped by biogeographic influences, disturbance regimes, and species adaptations to environmental conditions in the study area.

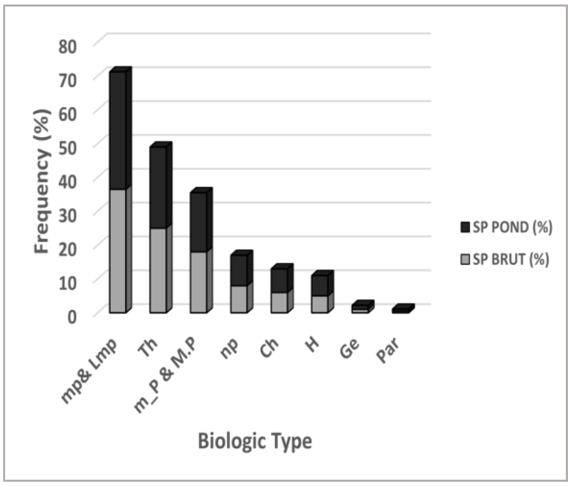

Figure 47: Biologic Types in Plant Community 2

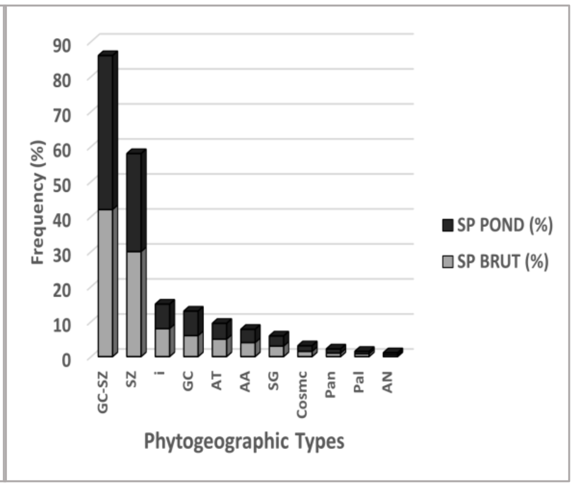

Figure 48: Phytogeographic Types in Plant Community 2

Plate 8: Life form and chorology spectra of species Biologic and Phytogeographic types among plant community in G2: Source; (Field survey, 2024)

Life Form and Chorology Spectra in Plant Community G3 (Wooded and Tree Savannah)

Figures 49 and 50 below are the raw and weighted spectra of the biological types of plant formation in ***group G3(wooded and tree Savannah)***. The combined microphanerophytes (mp) and lianas (Lmp) exhibit the highest frequency, indicating dominance in the vegetation structure. They represented 36.84% of the total raw spectra and an average cover of 36.14%. This shows that fires are infrequent in this area, allowing such species to thrive. Therophytes (Th) follow, with a raw spectrum of 17.54% and an average of 19.80%, indicating a significant presence, reinforcing the influence of seasonal disturbances, as these annual species complete their life cycles within a short period. Megaphanerophytes recorded a raw spectrum of 15.79% with an average coverage of 15.35 %, and nanophanerophytes recorded an 8.77% raw spectrum and an 11.88% average coverage. The raw spectrum of Chamaephytes was 8.77% and 10.40% average coverage. Hydrophyte species are poorly represented in raw and weighted spectra, likely reflecting the local arid environmental conditions and infrequent fire events.

The dominant phytogeographic distribution in this group is that of the Sudano-Zambezian species, with a raw spectrum of 38.60% and an average coverage of 37.50%. Guineo-Congolese/Sudano-Zambezian species are also strongly represented, with a raw spectrum of 33.33% and an average coverage of 30.77%. Species from the Atlantic domain and South Guinean regions are less frequent, likely due to their vulnerability to bushfires, which explains their reduced presence. This emphasises the dominance of fire-resistant Sudano-Zambezian species and the limited occurrence of fire-sensitive species, particularly from the Atlantic and South Guinean regions.

SP BRUT and SP POND values across biologic and phytogeographic categories illustrate the difference between raw species frequency and weighted ecological importance. The higher values in SP POND for dominant groups indicate that specific species exert more significant ecological influence despite their raw frequency being similar to others. This suggests that while several species may be present, only a subset plays a crucial role in defining the structure and function of the ecosystem. The results reinforce the significance of microphanerophytes, lianas, and fire-adapted species in shaping the plant community and highlight the role of biogeographic influences in determining species distribution.

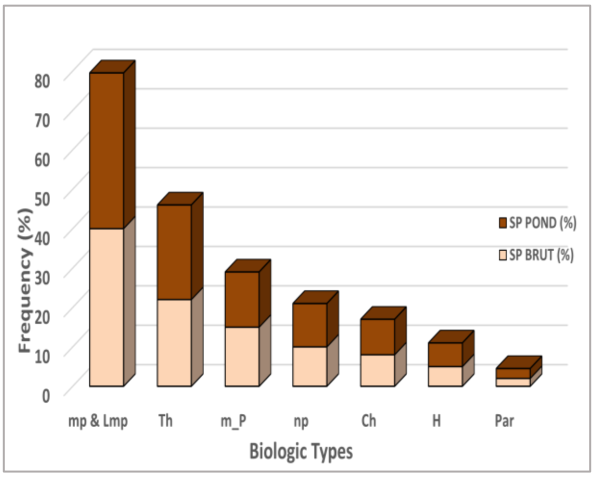

Figure 49: Biologic Types in Plant Community 3

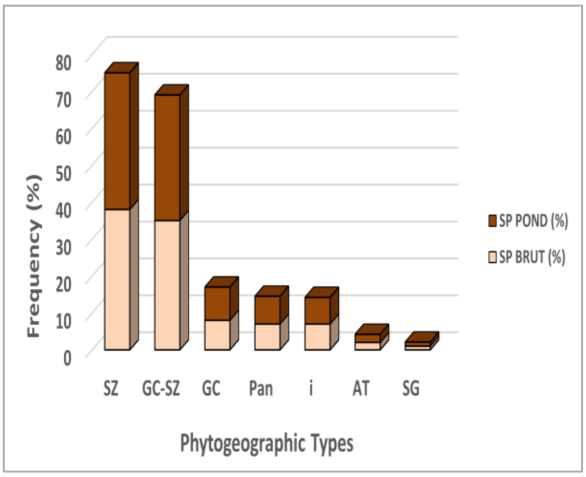

Figure 50: Biologic Types in Plant Community 3

Plate 9: Life form and chorology spectra of species Biologic and Phytogeographic types among plant community in G3: Source; (Field survey, 2024)

4.6.6. Diversity Structure Among the Plant Communities

Tree Height and DBH in an Open Forest Plant Community

A scatter plot analysis (***Figure 51***), was conducted to examine the relationship between total tree height (m) and diameter at breast height (DBH, cm). The logarithmic regression equation obtained was:

y= 1.5335ln(x) + 0.9597; where **y** represents total height and **x** represents DBH.

The coefficient of determination ($R^2 = 0.0538$) indicates a weak correlation between DBH and total height, suggesting that DBH alone is not a strong predictor of tree height in the study area. The data points show high variability, as reflected in the wide spread of values within the confidence ellipse. Some trees with similar DBH values exhibit significant differences in height, which could be attributed to species differences, site conditions, or environmental factors such as fire history and soil fertility. The weak correlation implies that other factors, such as species-specific growth patterns, competition, and site conditions, may be crucial in determining tree height beyond just DBH. Further analysis incorporating additional variables like age and environmental stressors may provide a more comprehensive understanding of tree growth dynamics.

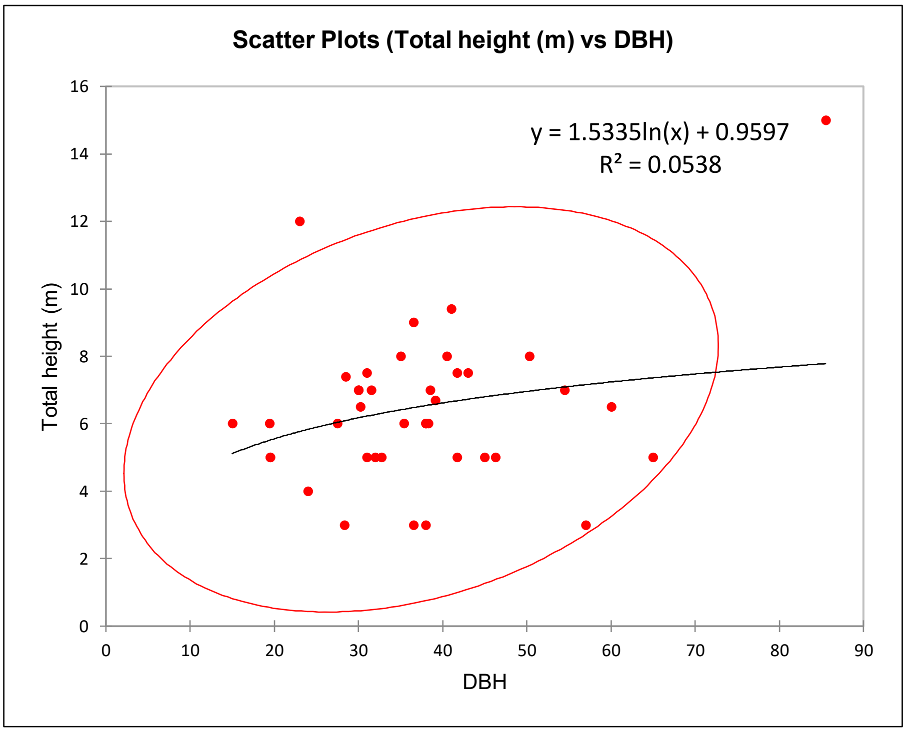

Figure 51: Relationship between Total Height and DBH (Diameter at Breast Height) for species in the open forest plots: Source; Field data (2024) / Generated from study data using Excel

Tree Height and DBH in Dry Forest and Mosaic Tree and Shrubby Savannah Community

Using a logarithmic regression model, a scatter plot was generated to assess the relationship between total tree height (m) and diameter at breast height (DBH, cm) (see ***Figure 52***). The regression equation obtained was: $y = 3.5876\ln(x) - 6.5993$

where y represents total height and x represents DBH.

The coefficient of determination ($R^2 = 0.3901$) indicates a moderate correlation between DBH and total height, suggesting that while DBH contributes to explaining variations in tree height, other factors may also influence height growth. The scatter plot shows a wide spread of data points, particularly at lower DBH values, indicating high variability in height for smaller trees. As DBH increases, tree height generally increases, but with diminishing returns, as seen in the curve leveling off at larger DBH values. This suggests that tree height growth slows as DBH increases, possibly due to species-specific growth patterns, environmental factors, or resource limitations. The confidence ellipse highlights the highest concentration of data points within the lower DBH range, suggesting that most trees sampled are in the smaller DBH classes. The presence of outliers at higher DBH values suggests variability in height among older or larger trees, potentially due to species differences, competition, or environmental stressors. The results indicate that DBH is a reasonable predictor of total tree height. However, other factors such as species type, site conditions, and fire history may also play significant roles in tree growth.

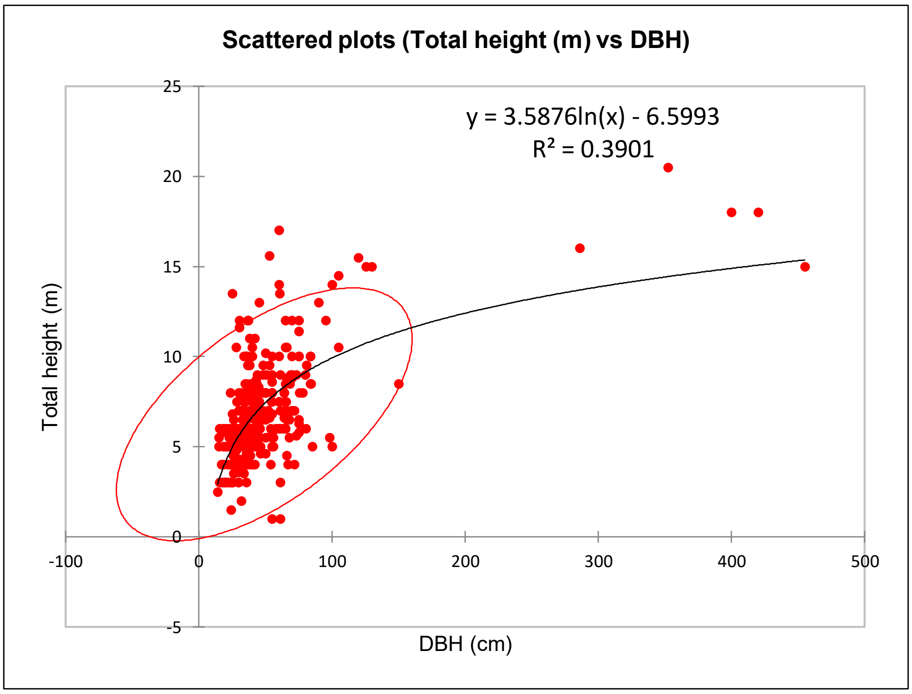

Figure 52: Scatter plot showing the relationship between Total Height (m) and DBH (cm) in Dry Forest and Mosaic Tree and Shrubby Savannah Community: Source; Field data (2024) / Generated from study data using Excel

Tree Height and DBH of Wooded and Tree Savannah Plant Community

The relationship between DBH and total height for species in this savannah, as shown in the scatter plot (***Figure 53***), follows a moderately strong logarithmic correlation ($R^2 = 0.5749$), with the trendline (y = 3.3488ln(x) - 5.5549) indicating that tree height increases with DBH. Using a logarithmic regression model, a scatter plot was generated to assess the relationship between total tree height (m) and diameter at breast height (DBH, cm). The scatter plot shows that tree height increases with DBH but at a diminishing rate, as the curve flattening at larger DBH values indicates. This pattern suggests that tree height growth slows as trees increase in diameter, possibly due to physiological constraints, resource allocation, or species-specific growth patterns. The confidence ellipse highlights that most data points are clustered within the lower DBH range, indicating that most trees sampled are relatively more minor. The presence of a few outliers at higher DBH values suggests that some larger trees exhibit varying heights, possibly due to species differences or environmental influences such as competition, fire impact, or soil conditions. The results indicate that while DBH strongly predicts total height, species characteristics, site conditions, and ecological disturbances may also play significant roles in tree growth.

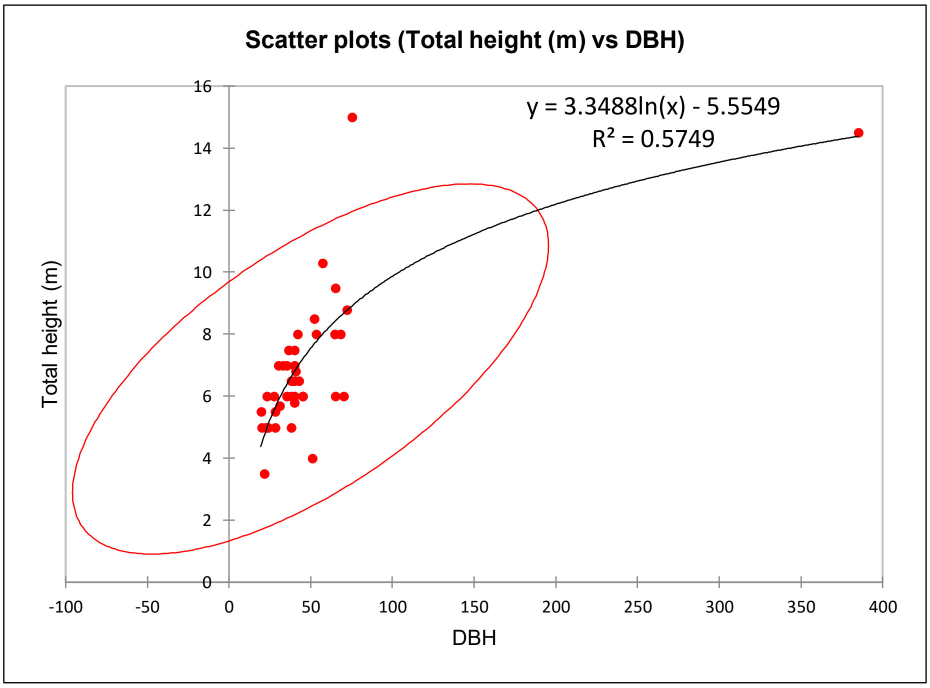

Figure 53: Scatter plot showing the relationship between Total Height (m) and DBH (cm) for species in the wooded and treed savanna community. Source: Field data (2024) / Generated from study data using Excel

Species Richness, Evenness and Abundance in Plant Communities

T***able 16*** below compares the Shannon Diversity Index and Pielou's Evenness and the standard deviation across the three plant community groups (G1, G2, and G3). The Shannon Diversity Index measures the overall species diversity within each group, while Pielou's Evenness indicates how evenly species are distributed. Although all groups exhibit relatively high diversity, variations in the Shannon Diversity Index indicate differences in species richness (the number of species present). Group 2 (G2) observed the highest Shannon diversity, suggesting that shrubby/tree savannahs support higher species richness, likely due to a mix of trees and shrubs adapted to frequent fires and human activities. Meanwhile, the relatively consistent evenness values suggest a similar proportional distribution of individuals among species across the groups despite differences in richness. The standard deviation also provided an insight into the variability of the Shannon Diversity Index and Pielou's Evenness across the different plant groups. The calculated standard deviation for the Shannon Diversity Index (1.06) indicates moderate variation among the groups. This suggests that while G2 exhibits the highest diversity (5.62), there is a noticeable spread in diversity across groups, reflecting differences in species richness and relative abundances. The standard deviation for Pielou's Evenness (0.01) is quite low, indicating that evenness is relatively stable across groups. This suggests that species in each group are distributed more uniformly despite differences in overall diversity. The low variability in evenness implies that disturbances such as wildfires or land-use changes may affect species richness more significantly than the relative distribution of species within these ecosystems.

Table 17: Shannon Diversity and Pielou's Evenness Across Plant Community Groups: A Comparison of Species Diversity and Distribution

GROUPS	SHANNON DIVERSITY INDEX	PIELOUS EVENNESS
G1	3.71	0.71
G2	5.62	0.71
G3	3.87	0.72
STANDARD DEVIATION	1.06	0.01

4.4.7. Land Use Land Cover and Vegetation Change and wildfire impact of ecosystems in Northern Ghana

The maps in this section show how the land cover types in this part of Ghana have changed over the past twenty years. They highlight variations in forest areas, shrublands, agroforestry fields, and human settlements. Looking at this data over time, we can understand how wildfires have spatially affected land use and ecosystems.

(**Plate 10 and Plate 11**) below reveals the distribution of LULC for 2000, 2005, 2010, 2015, and 2021 in northern Ghana. The details revealed inevitable discernible fluctuations throughout the years. The change in forest cover decreased steadily between 2000 and 2021. By 2021, there was a significant reduction, possibly due to deforestation, land conversion, or fire incidents. On the other hand, shrubby savannah increased consistently at the expense of the forest areas. This vegetation type dominated much of the landscape in 2021, indicating widespread degradation and conversion resulting from human activities and climate change. Agroforestry surface areas have increased over time. This reflects an intensification of agriculture and increased pressure on land for food production. However, water bodies in the entire period do not show any appreciable change, with only minor changes in the levels of the major rivers and reservoirs. The level of small water bodies could change due to conditions such as drought or flood. Human settlements show a conspicuous increase between 2001 and 2021 because of increases in urbanisation and population.

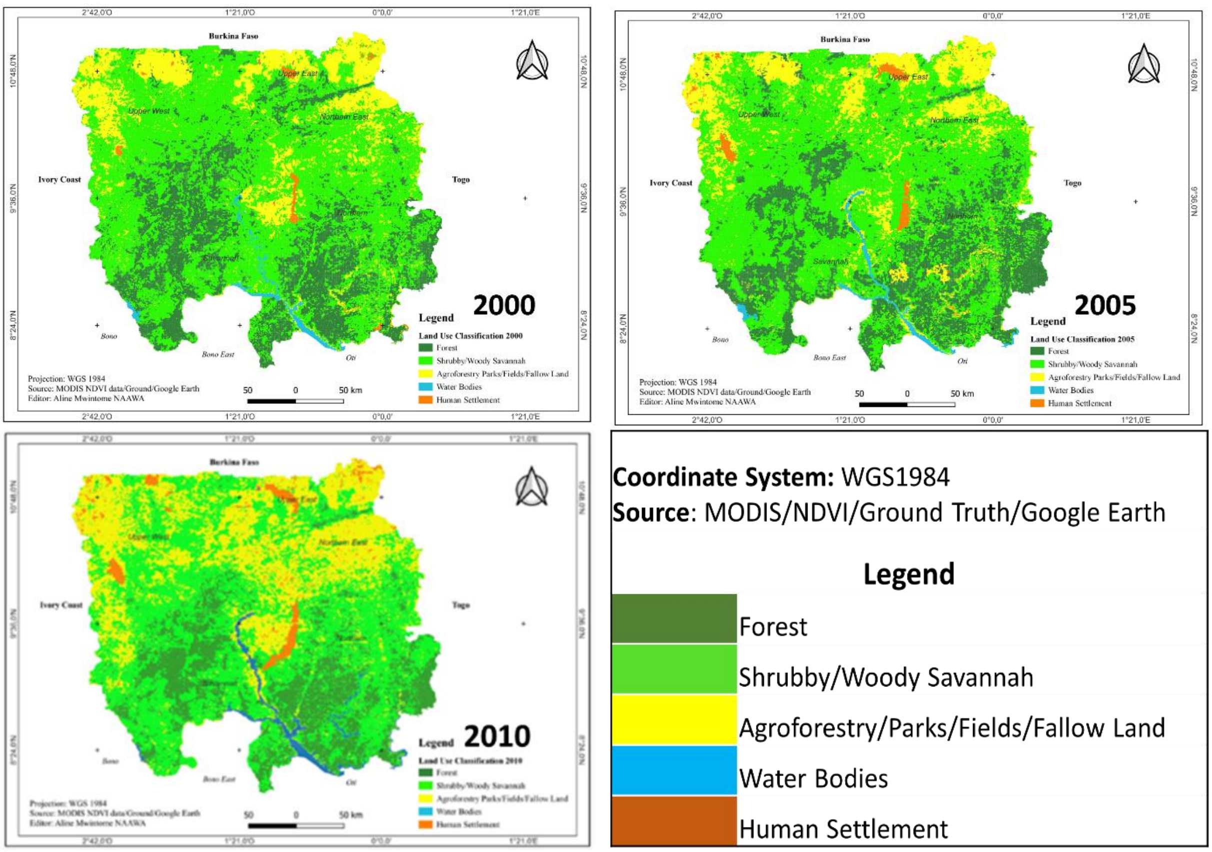

Plate 10: Land use and land cover (LULC) classification map for 2000,2005 and 2010 in the study area. Source: Retrieved from MODIS/NDVI data and Google Earth ground truth data

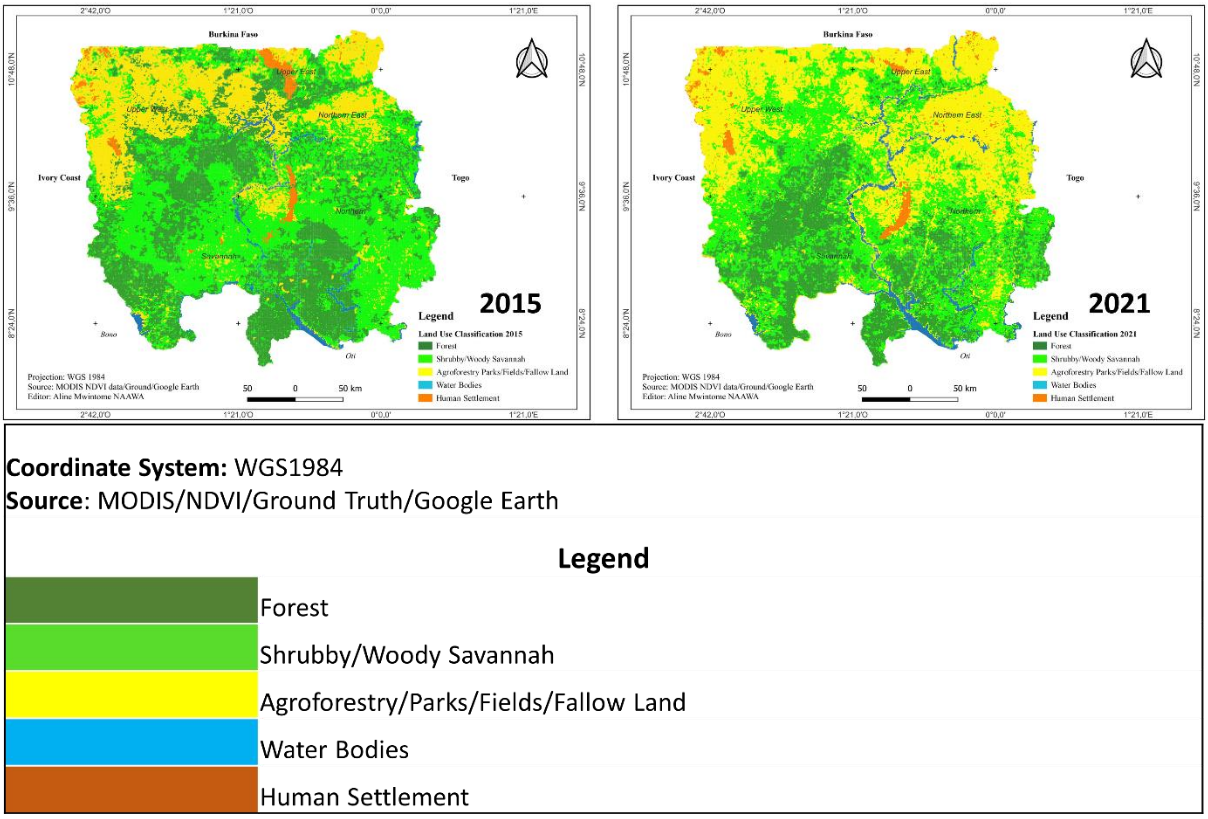

Plate 11: Land use and land cover (LULC) classification map for 2000,2005,2010,2015 and 2021 in the study area. Source: Retrieved from MODIS/NDVI data and Google Earth ground truth data

Changes in Forest Cover, Shrubby/Woody Savannah, Agroforestry, Fields, and Fallow Lands change, Changes in Water Bodies, Growth of Human Settlements

(Table 16) presents the changes in forest cover fluctuating over the study period, experiencing an overall decline of 10.86% from 23,718.33 km² in 2000 to 21,141.42 km² in 2021. A temporary increase in 2015 (30,699.47 km²) suggests potential reforestation efforts or natural regeneration. The shrubby/woody savannah also significantly declined by 38.82% from 57,225.12 km² in 2000 to 35,009.2 km² in 2021. A remarkable expansion was observed in agroforestry parks, fields, and fallow lands, increasing by 145.17% from 15,121.92 km² in 2000 to 37,074.08 km² in 2021. Water bodies also increased by 170.76%, from 995.37 km² in 2000 to 2,695.08 km² in 2021. Human settlement areas expanded the most, growing by 177.12%, from 643.93 km² in 2000 to 1,784.45 km² in 2021. ***Plates 10 and 11*** illustrate the increasing dominance of human settlements, particularly in the southern and central parts of the study area.

The observed trends emphasise a shift from natural vegetation (forest and woody savannah) to human-modified landscapes (agroforestry, settlements, and farmlands). The decline in natural vegetation suggests increasing anthropogenic pressures, likely exacerbated by climate change and wildfire occurrences. While seemingly positive, the expansion of water bodies may indicate alterations in hydrological patterns due to infrastructural developments such as dams and reservoirs.

Table 18: Changes in land cover types (Forest, Shrubby/Woody Savannah, Agroforestry parks/Fields/Fallow lands, Water Bodies, and Human Settlement) from 2000 to 2021

Land cover	2000	2005	2010	2015	2021	Percentage Change (2000-2021)
Forest	23718.33	23988.55	17648.43	30699.47	21141.42	-10.8647
Shrubby/Woody Savannah	57225.12	55633.51	47348.64	40049.35	35009.2	-38.822
Agroforestry parks/Fields/Fallow lands	15121.92	15750.15	28676.64	23293.56	37074.08	145.1679
WaterBodies	995.365	1092.645	1843.686	1961.839	2695.078	170.7628
Human Settlement	643.9349	1239.463	2186.646	1699.988	1784.454	177.1171

4.7. Discussion

This research examined how fires impact the composition of woody species, diversity, and vegetation structure of ecosystem services in the Savannahs of Ghana. The study also provided information on how fire affects species richness, family spectra, and life form distribution and influences the ability of species to recover during intense and frequent fires. The results indicate that fires significantly shape the structure and composition of Savannah ecosystems by influencing plant species and more significant ecological activities.

4.7.1. Fire Effects on Woody Species Composition

In the research conducted in the study area, a total of 123 species from 102 genera and 38 families were identified and recorded. The family Fabaceae emerged as the most widespread among them, possibly due to their nitrogen-fixing capability (Webb & Sprent, 2002). The results align with studies by Asase and Oteng Yeboah (2007) and Appiah (2013), which found that Fabaceae and Combretaceae are the most common plant families in the Savannah regions of Ghana. Fabaceae plants like *Vitellaria paradoxa* and *Parkia biglobosa* have progressively thick bark and regrowing traits after wildfires. Fire inadvertently shapes these ecosystems by favourably impacting the survival and development of species adapted to fire while negatively affecting vulnerable ones. According to this research paper's findings, certain species like

Vitellaria paradoxa, with an occurrence rate of 14%, are pyrophytic in nature and flourish in areas prone to frequent fires. Pyrophytic species have features like a thick bark and deep root systems that help them survive and bounce back from fires (Higgins et al., 2000). On the contrary, species vulnerable to fire struggle in areas of frequent burning due to intense competition. The interplay between fire-susceptible species plays a vital role in shaping the diverse ecosystem of the Savannah. This exchange leads to a mosaic of species that have adjusted to varying degrees of fire impact.

Vegetation Structure and Life Form Adaptations

The investigation of life form spectra revealed that fire tends to benefit certain species with specific physical characteristics, like small trees (microphanerophytes) and plants that complete their life cycle annually (therophytes). In areas with frequent fires, there was a noticeable abundance of microphanerophytes (constituting 35.% of the raw spectrum) along with therophytes (21.%), both of which have evolved well to cope with fire by regrowing quickly and sprouting again after disturbances (Bond & Keeley, 2005). The presence of these species plays a significant role in preserving the open landscape of the Savannah, where fires occur periodically, allowing the growth and dominance of grasses and shrubs. Mesophanerophyte plants (constituting 15.96 % of the diversity) thriving in non-burned areas indicate that suppressing fires allows taller trees to dominate. However, these trees often cannot withstand recurrent burns in wildfire-prone areas, leading to decreased tree density and a transition toward fire-resistant species. Previous studies have shown that fire plays a role in preventing closed canopy forests from forming in Savannah ecosystems by specifically decreasing the number of sensitive trees to fire (Sankaran et al., 2005). The research also found that species adapted to fire are prevalent in both burned and unburned areas, albeit to different extents. Plants such as *Vitellaria paradoxa* and *Parkia biglobosa* were commonly found throughout the area and had frequent wildfire occurrences. These species are ecologically and economically significant to the Savannah ecosystem due to their ability to withstand fire, thus playing a significant role in its ecological balance.

4.7.2. Fire and Phytogeographic Composition

The phytogeographic analysis showed that species from the Guineo Congolese/Sudanese Zambezi group (making up 41.64% of the spectrum) along with species from the Sudanese Zambezi group (29.91%) are the most prevalent in the research area. These species are well suited for the transition zone between forests and savannahs, where fires occur regularly. Their prevalence indicates their ability to withstand fires, which is consistent with the findings by

Sankaran et al. (2005), suggesting that plants adapted for fire-prone environments often dominate Savannah landscapes due to their resilience against disturbances. Compared to species found in wetter regions, the Guinean Congolese species were less common in the research area. They were noted as fire-sensitive and thrive in wooded habitats where fires occur less frequently. Their limited presence in the Savannah highlights how fire influences species distribution in various environments. Fire-resilient species thrive and take over areas that experience frequent fires, whereas fire-sensitive species are restricted to places with fewer occurrences of fires

Fire Frequency and Savannah Ecosystems in Northern Ghana

In Savannah ecosystems, fire plays a dual role. It can be both destructive and regenerative. Naturally occurring fires can result in a loss of biodiversity by wiping out fire-sensitive species; however, they also contribute to ecological diversity by creating habitat heterogeneity. In the areas under study, it was observed that fire affects the variety of species present and influences ecosystem functions. For instance, *Vitellaria paradoxa* and *Parkia biglobosa* provide ecosystem benefits such as fruit and nut production that are crucial for the local community's livelihoods. These species are greatly appreciated for their economic significance, particularly in producing export commodities such as shea butter (Yaro, 2008). Fires can improve ecosystem functions by keeping landscapes suitable for grazing and farming activities. Nevertheless, research attests that fires may diminish specific ecosystems by decreasing species richness and tree canopy coverage. This is a crucial consideration in land management to ensure a delicate balance between fire control methods and the preservation of ecosystem services for local communities.

4.7.3. Indicator Species and Adaptive Traits

The discovery of indicator species in this research sheds light on how Savannah ecosystems cope with fire disruptions and bounce back resiliently. Species such as *Vitellaria paradoxa* and *Parkia biglobosa* play roles in the ecosystem and act as indicators of resilience against fires. Their presence in areas that experience frequent wildfires indicates their ability to thrive under fire conditions, and their abundance can be tracked by monitoring changes in fire occurrence and intensity over time. Analysis of indicator species also helps recognise species particularly susceptible to fire disturbances. For instance, the study revealed that certain fire-sensitive species were less common in areas that experienced frequent burns, suggesting their susceptibility to shifts in fire regimes. This information is vital for conservation as it identifies species that might need safeguarding from the rising frequency of fires caused by climate change.

4.7.4. Fire, Human Activities, and Environmental Gradients

The research highlighted the intricate relationship between fire occurrences, human activities, and environmental elements. Areas with higher human activities, such as fires used for farming and charcoal production, significantly impacted the frequency and intensity of fire, altering the species composition and vegetation structure. Boateng (2017) observed that the intensification of land use in Ghana has resulted in more frequent fires and changes in Savannah dynamics. Using Detrended Correspondence Analysis (DCA) and Canonical Correlation Analysis (CCA), different plant communities were identified based on the level of fire intensity and human activity. The areas with frequent fires showed a more uniform fire-adapted species composition, whereas areas with fewer fires displayed higher species diversity/richness, including a diverse fire-sensitive species composition. These results emphasise the importance of implementing fire management approaches considering natural fire patterns and human-induced environmental adjustments.

4.7.5. Vegetation Dynamics: Expansion of Shrubby/Woody Savannah and Agroforestry Parks

Across the entire period of study, it is clear that the maps show a notable rise in shrubby and woody Savannah areas, particularly in both the northern and north-central parts of the area. This vegetation type is prone to fires and has grown larger while forests have been shrinking. The change is driven mainly by more frequent wildfires because people farm and animals graze more frequently (Archibald et al., 2012). Plants that are fire resistant, like *Combretum molle*, *Terminalia avicennioides*, and *Anogeissus leiocarpa*, tend to dominate this area now. These species are incredibly good at regenerating after fires due to their tough bark (Gindaba et al., 2005). On the other hand, this change in plant structure might threaten animals and plants that need the forest, especially those not adapted to frequent fires. Species like *Afzelia africana* and *Khaya senegalensis* are prone to fire harm, resulting in decreasing numbers within these impacted areas. These particular species usually do better in more damp and sheltered areas within untouched forests; they tend to have a hard time coming back to places dominated by fires. This situation puts them at risk of losing their homes and having less genetic variety (Nacoulma et al., 2011).

Additionally, the spread of agroforestry parks from 2006 onward highlights a move toward integrating farming practices with tree cover, especially in the southern and some parts of the northern areas. While these systems bring benefits like better soil quality and less erosion, they usually favour species that can handle fire well, such as *Vitellaria paradoxa* (shea tree) and *Parkia biglobosa* (African locust bean). These trees are often planted because they have some economic value. However, this change might result in the slow removal of forest species that are not as resistant to fire, which could more or less decrease plant diversity and affect the overall ecological balance in the region.

Human Settlement Growth and Its Impact on Species

One of the most significant shifts in land use changes observed between 2001 and 2022 could be the growth of human settlements, particularly in the Upper West, Upper East, and Northern regions. These settlement areas expanded considerably during this period, especially around major towns (GSS, 2021). A growth in population and migration patterns drives this urban expansion. Consequently, more land has been cleared for farming activities and infrastructure development. As a result, natural vegetation cover has diminished significantly, and ecosystems are becoming increasingly vulnerable to wildfires. Such changes tend to have substantial effects on biodiversity. For instance, species that are very sensitive to fire or habitat disturbances are affected. Reducing natural greenery due to expanding settlements negatively impacts species like *Vitellaria paradoxa* (the shea tree) and *Daniellia oliveri*. These plants are significant for local communities as they provide non-timber forest products essential for socio-economic reasons. However, the species seem threatened by ongoing land clearing for new developments alongside the growing incidence of wildfires in these disrupted areas (Boffa, 2000). The decline of such species can also lead to broader ecological consequences, such as decreasing the availability of vital ecosystem services such as soil stabilisation and water regulation (Bationo et al., 2012). Fire-tolerant species such as *Terminalia avicennioides* and *Combretum molle* are expected to dominate regions frequently exposed to fire. These species possess mechanisms like resprouting that allow them to survive and recover after fire events, making them more resilient in degraded landscapes (Sankaran et al., 2005). This shift in vegetation composition due to urban expansion and land-use change may result in a more homogenous landscape dominated by fire-adapted species, reducing overall ecosystem functioning (Scholes & Archer, 1997). The expansion of settlements also threatens the agroforestry systems that play a role in maintaining land sustainability in Northern Ghana. Trees like *Parkia biglobosa* and *Faidherbia albida* found in agroforestry parklands are vital for soil fertility and the well-being of communities (Leakey & Tchoundjeu, 2001). However, when these lands are converted for farming and urban expansion, the presence of these trees diminishes, which could result in reduced output and harm to the ecosystem (Mortimore & Turner, 2005).

4.7.6. Fire Regimes and Vegetation Dynamics

The observed shift from forested regions to shrubland and agroforestry parks between 2001 and 2022 is linked to evolving fire trends. More frequent and intense wildfires, often worsened by human activities like farming and the changing climate, have damaged wooded areas, encouraging the spread of species that can withstand fires while making it more challenging for the ecosystem to recover (Archibald et al., 2012). Fire-sensitive species such as *Vitellaria paradoxa* and *Daniella Oliveri* are important economically and ecologically, and they have declined in areas where fires have become more severe. These trees grow slowly and do not handle repeated burning and constant land clearing for agricultural purposes well (Boffa, 1999). Species like *Combretum molle* and *Annona senegalensis* that tolerate fire have proliferated in frequently burned environments. This has reduced the diversity of the vegetation, altered ecosystem functions, and resulted in the spread of shrublands and woody savannahs. Fire regimes have also contributed to the decline of species such as *Khaya senegalensis* and *Pterocarpus erinaceus.* This has reduced biodiversity and forest carbon storage, which has implications for climate change (Lal, 2004). Frequent fires have further degraded soils, diminishing the ecosystem's capacity to recover from disturbances and maintain long-term productivity (Scholes & Archer, 1997).

Ultimately, the transformation of fire regimes in the study area due to growth and climate change has paved the way for expanding species adapted to fires and significantly reshaping the composition and operation of the local ecosystem.

4.8. CONCLUSION

In conclusion, this research shows that fire impacts plant species' structure, composition and diversity in the Savannahs of northern Ghana. Frequent fires encourage the abundance of plants like *Vitellaria paradoxa* and *Parkia biglobosa,* while fire-sensitive species are less likely to thrive in areas that burn often. This interaction results in a mix of species that can adapt to varying levels of fire disturbance in the Savannah ecosystem. The study also points out the importance of fire in supporting ecosystem services like non-timber forest products and grazing areas in a balanced manner. However, the results indicate that more frequent fires influenced by natural and human causes could decrease species richness and alter vegetation structure, potentially threatening biodiversity and ecosystem services. These findings emphasise the importance of adaptive fire management strategies that weigh the advantages of fire against the necessity to safeguard biodiversity and ecosystem services from a conservation and land management standpoint. Further studies should delve into the lasting impacts of changing fire regimes on Savannah environments over time, especially considering climate change and land use intensification. By grasping the complex interactions between fire occurrences, species composition, and ecosystem services, we can devise effective strategies for handling fires within Ghana's northern Savannah ecosystems.

GENERAL CONCLUSION AND RECOMMENDATION

CONCLUSION

The results of this study represent a comprehensive understanding of the multifaceted impacts of wildfires on ecosystem services, species composition, and fire dynamics in the Northern Savannah of Ghana (a mosaic of natural and human-modified landscapes). Natural savannahs, characterised by open woodlands and grasslands, have evolved with fire as a natural regulator, maintaining biodiversity through low-intensity seasonal burns that recycle nutrients, suppress woody encroachment, and stimulate germination of fire-adapted species. However, anthropogenic savannahs, shaped by centuries of human activity, reflect a transformed reality where agricultural expansion, charcoal production, and settlement growth have altered fire regimes. These human-altered landscapes now face compounded pressures from climate change, leading to fire patterns that increasingly deviate from historical norms.

This work is founded on three central tenets: assessing the management strategies employed to deal with wildfires, identifying wildfire drivers, and analysing their effect on species composition. This study unravels the complex interplay of natural processes and human interventions that define the region's fire dynamics. By testing hypotheses related to these objectives, the research advances scientific understanding and provides actionable insights for balancing ecological resilience with socioeconomic needs.

The first objective of this study assessed wildfire management strategies at local and national levels, revealing a fragmented yet evolving landscape of practices. Traditional fire management, rooted in indigenous knowledge, remains deeply embedded in rural communities. Practices such as controlled early dry season burns, designed to reduce fuel loads and prevent catastrophic late season fires, reflect generations of ecological wisdom. However, the effectiveness of these methods is increasingly strained by climate change, which has intensified fire weather conditions, prolonged droughts, higher temperatures, and erratic rainfall. National policies, such as the National Wildfire Management Policy (NWMP) and institutional efforts by the Forestry Commission and Environmental Protection Agency, provide a regulatory framework for fire suppression and prevention. Yet, these top-down approaches often falter due to inconsistent enforcement, limited funding, and inadequate integration of local knowledge.

Technological advancements, particularly remote sensing and GIS, have emerged as powerful tools for fire monitoring and early detection. Satellite data from MODIS and Sentinel2 enabled precise mapping of fire hotspots and burned areas, offering real-time insights into fire spread and intensity. However, the study found that technological solutions alone cannot address the root causes of wildfires. While policies and technology provide critical infrastructure, their disconnect from community realities undermines resilience. For instance, fire bans during peak agricultural seasons often clash with subsistence farmers' reliance on fire for land clearance, leading to unintended consequences like illegal burning. Thus, the study concludes that adaptive fire management must harmonise scientific innovation with community-driven practices, ensuring ecologically sound and socially equitable policies.

The second objective identified the drivers of wildfires, testing hypotheses on the roles of climate change and human activity. Climatic factors, including a 1°C temperature rise since 1960 and increasingly erratic rainfall, have extended the fire season and heightened fuel aridity. Statistical analysis confirmed that maximum temperature ($p < 0.01$) and reduced humidity significantly correlate with fire frequency, as warmer, drier conditions amplify vegetation flammability. These findings align with global climate-driven fire risk patterns, emphasising the vulnerability of semiarid ecosystems like the Northern Savannah. Human activities, however, emerged as equally critical drivers. Spatial analysis using Geographically Weighted Regression (GWR) revealed that over 70% of fires cluster within 5 km of settlements and agricultural zones. West Gonja and Mamprugu Moagduri are identified as high-risk areas due to intensive farming and pastoralism. Practices such as slash-and-burn agriculture, hunting, and charcoal production ignite fires and fragment landscapes, creating corridors for fire spread. The hypothesis that proximity to human activity drives wildfire occurrence is unequivocally supported: anthropogenic ignition sources, compounded by land-use changes, overshadow natural causes like lightning.

Yet, the study also uncovered distinctions in fire trends. While the Mann-Kendall test detected a significant decline in burned areas over time ($p = 0.015$), attributed to improved firefighting capacity and awareness, fire frequency showed no clear trend ($p = 0.499$). This paradox highlights persistent challenges: even as management efforts reduce fire spread, ignition pressures from population growth and land use intensification remain unmitigated. The interplay of climate and human drivers thus creates a feedback mechanism where degraded ecosystems become more fire-prone, further exacerbating land degradation.

The third objective examined wildfire impacts on species composition and ecosystem processes, testing hypotheses about vegetation shifts and biodiversity decline. Frequent fires have profoundly altered the savannah ecosystem in northern Ghana. Fire-tolerant species, such as *Vitellaria paradoxa* and *Parkia biglobosa*, now dominate burned areas, their thick bark and resprouting abilities offering survival advantages. Fire-sensitive species like *Khaya senegalensis* and *Pterocarpus erinaceus* have declined by up to 60% in frequently burned zones, reflecting biodiversity loss. The hypothesis that fires reduce species richness is strongly validated: a 15% decline in plant diversity was documented in fire-affected areas, with cascading effects on biodiversity. The transformation extends beyond species composition. Repeated burns have driven a structural shift from closed woodlands to open shrublands, disrupting ecological functions. These changes disproportionately impact anthropogenic savannahs, where overlapping pressures, fire, overgrazing, and deforestation—accelerate land degradation. Natural savannahs, though more resilient, face similar threats as fire frequencies exceed historical norms, weakening their capacity to regenerate.

This study confirms that climatic changes, inadequate fire management strategies, and human activities drive wildfire regimes, destabilising ecosystems and livelihoods. Hence, this study offers a roadmap for resilience. By embracing adaptive strategies that blend tradition with innovation, prioritise equity and foster collaboration, Ghana can navigate the dual imperatives of ecological preservation and human wellbeing. The savannah's future hinges on recognising fire not merely as a threat but as a force that, when wisely managed, can sustain both people and nature in a changing world. The resulting shifts in vegetation dynamics and ecosystem services call for urgent policy interventions. Strengthened wildfire management, improved enforcement of existing policies, and enhanced integration of remote sensing technologies to mitigate wildfire risks. Future research should focus on the long-term ecological impacts of changing fire regimes, particularly in the context of climate change and land-use intensification. By understanding the intricate relationships between wildfires, biodiversity, and ecosystem resilience, sustainable fire management solutions can be developed to protect Ghana's savannah ecosystems for future generations.

RECOMMENDATIONS

A comprehensive approach integrating community participation, policy enforcement, scientific research, and technological advancements is essential to effectively managing wildfires and mitigating their impact on savanna ecosystems. Strengthening wildfire management strategies at both local and national levels, addressing the key drivers of wildfires, and minimising their effects on ecosystem structural diversity are critical steps toward building resilience in fire-prone areas.

At the local and national levels, wildfire management should prioritise community-based fire prevention initiatives that engage local populations in fire awareness campaigns, firefighting training, and the establishment of community fireguards. Incorporating indigenous knowledge into fire management practices can enhance controlled burning strategies and improve land-use sustainability. Stronger enforcement of wildfire control policies, such as the National Wildfire Policy and Bushfire Prevention and Control Act, is also necessary to regulate land burning and deter illegal fire use. Technological advancements, including Geographic Information Systems (GIS), remote sensing, and drones, should be leveraged for early wildfire detection, real-time monitoring, and mapping of high-risk zones. Collaborative efforts among government agencies, non-governmental organisations, and local authorities can promote sustainable land management practices that reduce fire hazards. Given the increasing impact of climate change, wildfire strategies must also be adapted to address longer dry seasons and rising temperatures, ensuring that fire management aligns with broader climate adaptation policies.

Understanding the underlying causes of wildfires is crucial to effective mitigation. Climate factors such as rising temperatures, prolonged dry seasons, and erratic rainfall patterns have intensified fire risks, making ecosystems more vulnerable. However, human activities remain a dominant driver of wildfires, particularly through agricultural expansion, land clearing, hunting, and settlement encroachment. Certain land-use practices in savanna grasslands and shrublands contribute to higher fuel loads, increasing the likelihood of fires. Topography also plays a role, with elevation, slope, and wind exposure influencing fire spread and severity. Additionally, proximity to human settlements increases the frequency of wildfires, as illegal burning and accidental ignitions remain common in these areas.

The effects of wildfires on savanna ecosystem structural diversity are significant and long-lasting. Frequent fires contribute to the decline of tree cover, causing a shift from woodland to grassland ecosystems. This transition alters species composition, with fire-resistant species such as *Vitellaria paradoxa* and *Parkia biglobosa* becoming more dominant, while fire-sensitive species decline. Biodiversity loss is another major consequence, as repeated fires disrupt ecological balance, reduce species richness, and degrade habitat structures. Soil health is also negatively affected, with wildfires depleting essential nutrients, decreasing fertility, and increasing erosion, leading to long-term vegetation loss. Moreover, these changes reduce carbon sequestration capacity, as tree cover loss weakens the savanna ecosystem's ability to store carbon, further exacerbating climate change.

By integrating community-driven initiatives, scientific advancements, and policy enforcement, wildfire management strategies can more effectively reduce fire risks while promoting ecological sustainability in savanna landscapes.

LIMITATIONS OF THE STUDY

This study aims to offer a thorough analysis of wildfire effects on ecosystems in Ghana's northern Savannah ecological zone. However, several limitations must be acknowledged, and strategies to address them should be outlined to ensure the robustness and reliability of the findings:

1. Data Availability and Quality: Historical fire data and comprehensive assessments of ecosystem services in the region may be inconsistent or incomplete, affecting the accuracy of the analysis. The study used data sources, including satellite imagery, government records, and local surveys, to cross-validate information. In cases where data gaps are unavoidable, some assumptions were made and stated transparently. Also, statistical methods were used in some instances to account for uncertainties, ensuring a more reliable analysis.
2. Temporal and Spatial Scale: The study's fixed geographical location and specific time frame may limit the generalizability of its findings to other regions or periods. Hence, the results were contextualised within broader regional and global trends, allowing for a discussion of how the specific spatiotemporal context might influence the interpretation and application of the findings in different settings.
3. Complex Interactions: The interactions between wildfires, climate change, and ecosystem services are inherently complex and non-linear, making them difficult to quantify accurately, hence the use of statistical modelling to capture these interactions
4. Technological Constraints: The resolution and frequency of satellite imagery may limit the detection of small-scale fires or subtle changes in vegetation, potentially leading to underestimation of fire impacts. This is why the study incorporated ground-based observations and local knowledge wherever possible. The methodology and results sections explicitly state the limitations of the technology used, ensuring transparency in the study’s approach.

By acknowledging these limitations and providing some solutions, this study aims to provide a more detailed and transparent analysis of the wildfire effects on ecosystem services in the northern Savannah zone of Ghana. This approach will facilitate a more informed interpretation and application of the research findings, contributing valuable insights to academic discourse and policy development.

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ANNEXES

SURVEY QUESTIONNAIRE:

Ph.D. Candidate on Climate Change and Disaster Risk Management

This research is for a student from the University of Lome studying for a Ph.D. in Climate Change and Disaster Risk Management. The questionnaire is designed for research on the effects of wildfire on ecosystems in Ghana's savannah ecological zone under a changing climate. The answers provided, therefore, shall be treated confidentially, with the assurance that there are no good or bad answers. May I proceed with the interview, please?

No. of the questionnaire .... Date ....

A. PERSONAL INFORMATION

1. Gender: a- Male .... b- Female ....

2. Age:……………………………………………………...

3. Occupation:

a. Farmer ....b. Housewife……………………………….

c. Official...d. Student…………………………………

e. Unemployed…………………………………f. Others …………………………….

4. Habitation:

Are you from this community, or are you a visitor……………………………………………..?

How long have you lived in the community...?

B. KNOWLEDGE OF ECOSYSTEMS AVAILABLE

5. Natural Resources available in the community

a-Trees…………………...b-Water bodies…………………………...

d-Forest…………………c- Land………………………… e-Others…………….

Agricultural Practiced by the Population

6. Which types of activities do you (or your family) practice:

B- Farming...C- Tree crops growing................................

D- Livestock (cattle, sheep, goats) breeding.............E -Others...

7. All produce grown is intended for:

A- Family consumption purposes (Subsistence agriculture) ....

B- Sale or trade ....

C. KNOWLEDGE OF WILDFIRES

8. Do you know the situation of wildfires?

Yes …………………………………. No ……………………………………

9. Do you feel that the number of wildfires in your community is:

A- Increasing................................ B- Decreasing .... C- Constant ....

10. Have you ever witnessed wildfires?

Yes ……….. ...... No
…………………………………………......

11. Which resources are usually affected by fires in your community?

…………………………………………………………………………………………

12. To what extent are these fires?

Less than 1 ha .... Less than 50 ha ....More than 100 ha ....

D. UNDERLYING CAUSES OF WILDFIRES

13. Do you think Climate change is a major cause of wildfires?

Yes…………………………………..…………. No……………………….………

If yes, how……………………………………………………………………….

14. What time of the year do you experience wildfires?

Rainy season .... Dry Season........................... Any point in time…………..........

15. Are there some human activities contributing to wildfires in your community?

Yes... No ....…

If yes, Kindly list them………………………………………………………………………………………………

16. What things/factors influence the behaviour of fire, in your opinion?

…………………………………………………………………………………………………

17. Among these factors, which are the most important or influential?

…………………………………………………………………………………………………

18. In your opinion, what do you think are the main causes of wildfires:

a-Humans ....b-Climate ....

E. EFFECTS OF WILDFIRES

19. What is the magnitude of the impact of wildfires?

A-severe………...B-very severe……. C-less severe………. D-minimal……………

20. Have ecosystem resources changed over the years due to wildfires?

6. **A**-Decreasing…………………. B-Increasing…………………………...

21. In your opinion, what damages or ways do fires affect productivity?

Houses ....Fields ....Herds.............................

Extinction of some plants and animals .... Human life.... ....Others ....

Thank you for your participation

FLORA CHECKLIST

Number	Species	Genra	Family	Life form type	Chorological type
1	*Acacia dudgeon* Crai b.	Acacia	Fabaceae	mp	SZ
2	*Acacia gourmaensis* A. chev	Acacia	Fabaceae	mp	SZ
3	*Acacia mellifera* (Vahl) Benth	Acacia	Fabaceae	mp	SZ
4	*Acacia nilotica*	Acacia	Fabaceae	mp	SZ
5	*Acacia seyal* Del.	Acacia	Fabaceae	mp	SZ
6	*Adansonia digitata* L.	Adansonia	Malvaceae	m_P	SZ
7	*Afzelia Africana* Smith ex Pers.	Afzelia	Fabaceae	m_P	GC-SZ
8	*Albizia coriaria* Oliv.	Albizia	Fabaceae	m_P	GC-SZ
9	*Amaranthus* hybridus L.	Amaranthus	Amaranthaceae	Th	AT
10	*Anacardium occidentale* L.	Anacardium	Anacardiaceae	mp	i
11	*Aneilema* sp.	Aneilema	Commelinaceae	Ch	SZ
12	*Anogeissus leiocarpus* (DC) Gill. & Perr.	Anogeissus	Combretaceae	m_P	SZ
13	*Aristida verstingii*	Aristida	Poaceae	mp	SZ
14	*Arundinella pumila*	Arundinella	Poaceae	H	GC-SZ
15	*Aspilia africana* (Pers.) C.D. Adams.	Aspilia	Asteraceae	Th	SG
16	*Asystasia gangetica* (L.) T. Anders.	Asystasia	Acanthaceae	np	GC-SZ
17	*Azadirachta indica* Juss	Azadirachta	Meliaceae	mp	i
18	*Balanites aegyptiaca* (L.) Del	Balanites	Zygophyllaceae	mp	SZ
19	*Bauhinia variegata* Spp.	Bauhinia	Fabaceae	mp	SZ
20	*Blighia sapida*	Blighia	Fabaceae	mp	GC-SZ
21	*Boerhavia diffusa*	Boerhavia	Nyctaginaceae	Th	Cosmc
22	*Bombax costatum* Pellegr. & Vuillet	Bombax	Malvaceae	mp	SZ
23	*Boswellia dalzielli*	Boswellia	Burseraceae	mp	SZ

24	*Burkea africana* Hook	Burkea	Fabaceae	mp	SZ
25	*Cassia sieberiana*	Cassia	Fabaceae	mp	GC-SZ
26	*Ceiba pentandra* (L.) Gaertn.	Ceiba	Malvaceae	M.P	GC-SZ
27	*Celtis intergrifolia*	Celtis	Ulmaceae	mp	SZ
28	*Cephalanthus occidentalis*	Cephalanthus	Rubiaceae	Th	GC-SZ
29	*Chloris pilosa* Schmach.	Chloris	Poaceae	Th	GC
30	*Cleome rutidosperma* DC.	Cleome	Cleomaceae	Th	GC
31	*Combretum collinum* Fresen.	Combretum	Combretaceae	mp	GC-SZ
32	*Combretum glutinosum*	Combretum	Combretaceae	mp	SZ
33	*Combretum molle*	Combretum	Combretaceae	mp	SZ
34	*Commelina* sp	Commelina	Commelinacea e	Ch	GC-SZ
35	*Commiphora Kerstingii* Engl.	Commiphora	Burseraceae	mp	GC-SZ
36	*Corchorus aestuans*	Corchorus	Malvaceae	Th	GC-SZ
37	*Corchorus Olitorius*	Corchorus	Malvaceae	Th	GC-SZ
38	*Cordia Myxa*	Cordia	Boraginaceae	mp	Pal
39	*Cordia sinensis Lam.*	Cordia	Cordiaceae	np	GC
40	*Croton lobatus L.*	Croton	Euphorbiaceae	Th	GC-SZ
41	*Cynodon dactylon* (L.) Pers.	Cynodon	Poaceae	Ch	GC-SZ
42	*Cyperus rotundus*	Cyperus	Cyperaceae	H	GC-SZ
43	*Cyperus strigosus*	Cyperus	Cyperaceae	Ge	Pan
44	*Dactyloctenium aegyptium* (L.) P. Beauv.	Dactylocteniu m	Poaceae	H	GC-SZ
45	*Daniellia oliveri* (Rolfe) Hutch. & Dalziel	Daniellia	Fabaceae	m_P	GC-SZ
46	*Desmodium scorpiurus* (Sw.) Desv.	Desmodium	Fabaceae	Ch	GC-SZ
47	*Detarium microcarpum* G. and Perr	Detarium	Fabaceae	mp	SZ
48	*Detarium senegalense*	Detarium	Fabaceae	m_P	GC-SZ
49	*Digitaria sanguinalis* (L.) Scop.	Digitaria	Poaceae	np	AN
50	*Diospyros mespiliformis* Hochst Ex. A. Rich	Diospyros	Ebenaceae	mp	GC-SZ

51	*Diospyros virginiana*	Diospyros	Ebenaceae	m_P	SZ
52	*Dissotis rotundifolia* (Sm.) Triana.	Dissotis	Herbaceous	Ch	GC-SZ
53	*Eclipta alba* (L.) L.	Eclipta	Asteraceae	Th	GC-SZ
54	*Eleusine indica* (L.) Gaertn.	Eleusine	Poaceae	Th	GC-SZ
55	*Entada Africana* Guill. & Perr	Entada	Fabaceae	Lmp	SZ
56	*Eragrostis tenella* (L.) P Beauv.	Eragrostis	Poaceae	Th	GC-SZ
57	*Euphorbia hirta* L.	Euphorbia	Euphorbiaceae	Th	GC-SZ
58	*Faidherbia albida* (Delile) A. Chev.	Faidherbia	Fabaceae	m_P	SZ
59	*Gardenia ternifolia* Schum, & Thonn	Gardenia	Rubiaceae	np	GC-SZ
60	*Gmelina arborea* Roxb.	Gmelina	Verbenaceae	m_P	i
61	*Haematostaphis* barteri Hook.f.	Haematostaphis	Anacardiaceae	m_P	SZ
62	*Hexalobus monopetalus* Engl. & Diels	Hexalobus	Anonaceae	mp	SZ
63	*Hibiscus* surattensis	Hibiscus	Malvaceae	Ch	Pan
64	*Isoberlinia doka* Crai b.& Stapf.	Isoberlinia	Fabaceae	m_P	SZ
65	*Isoberlinia tomentosa* (Harms) Craib & Stapf	Isoberlinia	Fabaceae	m_P	SZ
66	*Khaya ivorensis*. A.Chev	Khaya	Meliaceae	M.P	GC
67	*Khaya senegalensis* (Desr.) A. Juss	Khaya	Meliaceae	m_P	GC-SZ
68	*Lannea acida* Engl. &. Krause	Lannea	Anacardiaceae	mp	GC-SZ
69	*Lannea Barteri* (Oliv.) Engl.	Lannea	Anacardiaceae	mp	GC-SZ
70	*Lannea microcarpa* Engl. & K. Krause	Lannea	Anacardiaceae	mp	SZ
71	*Laportea aestuans* (L.) Chew.	Laportea	Urticaceae	Th	GC
72	*Leptocholoa chinensis* (L.) Nees.	Leptocholoa	Poaceae	H	Pan

73	*Luffa cylindrical* (L.) Roem.	Luffa	Cucurbitaceae	Lmp	i
74	*Malvastrum coromandelianum* (L.) Garcke.	Malvastrum	Malvaceae	np	GC
75	*Mangifera indica* L.	Mangifera	Anacardiaceae	m_P	i
76	*Markhamia tomentosa*(Benth.) K. Schum.ex Engl.	Markhamia	Cucurbitaceae	mp	GC
77	*Megathyrsus* maximus	Megathyrsus	Poaceae	H	GC
78	*Mimosa* pudica L.	Mimosa	Fabaceae	Th	i
79	*Momordica* charantia L.	Momordica	Cucurbitaceae	Lmp	GC-SZ
80	*Moringa oleifera* Lam	Moringa	Moringaceae	mp	i
81	*Nauclea Latifolia* Sm.	Nauclea	Rubiaceae	mp	GC-SZ
82	*Ocimum* tenuiflorum	Ocimum	Lamiaceae	np	Pal
83	*Oldenlandia corymbosa* L.	Oldenlandia	Rubiaceae	Th	GC-SZ
84	*Oxalis corniculata* L.	Oxalis	Oxalidaceae	Ch	GC
85	*Oxalis stricta* L.	Oxalis	Oxalidaceae	Ch	GC
86	*Ozoroa insignis* Del.	Ozoroa	Anacardiaceae	np	SZ
87	*Panicum* maximum	Panicum	Poaceae	H	GC
88	*Parkia biglobosa* (Jcq.) R. Br. ex G. Don	Parkia	Fabaceae	mp	AT
89	*Paspalum* scrobiculatum	Paspalum	Poaceae	H	GC-SZ
90	*Pennisetum polystachion* (L.) Schult.	Pennisetum	Poaceae	Th	GC-SZ
91	*Pennisetum* purpurreum	Pennisetum	Poaceae	H	GC
92	*Phyllanthus amarus* Suhum & Thonn.	Phyllanthus	Euphorbiaceae	Th	GC
93	*Physalis Peruviana*	Physalis	Solanaceae	Th	Pan
94	*Piliostigma reticulatum* (DC.) Hochst.	Piliostigma	Fabaceae	np	GC-SZ
95	Piliostigma thonningii	Piliostigma	Fabaceae	np	GC-SZ
96	*Pterocarpus erinaceus* Poir.	Pterocarpus	Fabaceae	mp	SZ
97	*Rottboellia cochinchinensis*	Rottboellia	Poaceae	Th	GC-SZ

98	*Saba senegalensis* (A. DC.) Pichon	Saba	Apocynaceae	Lmp	AA
99	*Sacciolepis africana* C.E. Hubbard & Snowden.	Sacciolepis	Poaceae	H	GC-SZ
100	*Setaria barbata* (Lam.) Kunth	Setaria	Poaceae	H	GC-SZ
101	*Sida acuta* Burm.F	Sida	Malvaceae	np	GC-SZ
102	*Spigella anthelmia* L.	Spigella	Loganiaceae	Th	AA
103	*Sporobulus* pyramidalis	Sporobulus	Poaceae	H	SZ
104	*Sterculia setigera* Del.	Sterculia	Malvaceae	m_P	SZ
105	*Sterculia tragacantha* Lindl.	Sterculia	Malvaceae	m_P	SZ
106	*Stereosperemum* kunthiamum Cham.	Stereosperemum	Bignoniaceae	mp	SZ
107	*Striga hermontrica*	Striga	Orobanchaceae	Par	SZ
108	*Stylosanthes Mucronata*	Stylosanthes	Fabaceae	Ch	GC-SZ
109	*Synedrella nodiflora* (L.) Gaertn.	Synedrella	Asteraceae	Th	GC-SZ
110	*Tamarindus indica* L.	Tamarindus	Fabaceae	mp	GC-SZ
111	*Tectona grandis* L.f.	Tectona	Verbenaceae	M.P	i
112	*Terminalia albida* Sc. Elliot	Terminalia	Combretaceae	mp	SZ
113	*Terminalia avicennioides* Guill. & Per	Terminalia	Combretaceae	m_P	SZ
114	*Terminalia glaucescens* Planch. ex Benth.	Terminalia	Combretaceae	mp	SZ
115	*Trianthema* sp. L.	Trianthema	Aizoaceae	Ch	GC-SZ
116	*Tridax procumbens* L.	Tridax	Asteraceae	Ch	GC-SZ
117	*Triumfetta dubia*	Triumfetta	Malvaceae	Ch	Pan
118	*Vernonia cinerea* (L.) Lesss	Vernonia	Asteraceae	np	GC-SZ
119	*Vetiveria nigritana*	Vetiveria	Poaceae	H	GC-SZ
120	*Vitellaria paradoxa* C.F.Gaertn	Vitellaria	Sapotaceae	mp	SZ
121	*Vitex doniana* Sweet	Vitex	Verbenaceae	mp	GC-SZ
122	*Zanthoxylum zanthoxyloides* (Lam.) Zepern. & Timler	Zanthoxylum	Rutaceae	mp	GC-SZ
123	*Ziziphus mauritiana*	Ziziphus	Rhamnaceae	mp	SZ

PYROPHYTES CHECKLIST

Num	Species	Genra	Family	Life type	Life form type	Chorological type
1	*Acacia dudgeon* Crai b.	Acacia	Fabaceae	Ligneous	mp	SZ
2	*Acacia gourmaensis* A. chev	Acacia	Fabaceae	Ligneous	mp	SZ
3	*Acacia mellifera* (Vahl) Benth	Acacia	Fabaceae	Ligneous	mp	SZ
4	*Acacia nilotica*	Acacia	Fabaceae	Ligneous	mp	SZ
5	*Acacia seyal* Del.	Acacia	Fabaceae	Ligneous	mp	SZ
6	*Adansonia digitata* L.	Adansonia	Malvaceae	Ligneous	m_P	SZ
7	*Afzelia Africana* Smith ex Pers.	Afzelia	Fabaceae	Ligneous	m_P	GC-SZ
8	*Anogeissus leiocarpus* (DC) Gill. & Perr.	Anogeissus	Combretaceae	Ligneous	m_P	SZ
9	*Azadirachta indica* Juss	Azadirachta	Meliaceae	Ligneous	mp	i
10	*Balanites aegyptiaca* (L.) Del	Balanites	Zygophyllaceae	Ligneous	mp	SZ
11	*Bombax costatum* Pellegr. & Vuillet	Bombax	Malvaceae	Ligneous	mp	SZ
12	*Burkea africana* Hook	Burkea	Fabaceae	Ligneous	mp	SZ
13	*Combretum collinum* Fresen.	Combretum	Combretaceae	Ligneous	mp	GC-SZ
14	*Combretum glutinosum*	Combretum	Combretaceae	Ligneous	mp	SZ
15	*Combretum molle*	Combretum	Combretaceae	Ligneous	mp	SZ
16	*Daniellia oliveri (Rolfe)* Hutch. & Dalziel	Daniellia	Fabaceae	Ligneous	m_P	GC-SZ
17	*Detarium microcarpum* G. and Perr	Detarium	Fabaceae	Ligneous	mp	SZ
18	*Detarium senegalense*	Detarium	Fabaceae	Ligneous	m_P	GC-SZ
19	*Diospyros mespiliformis* Hochst Ex. A. Rich	Diospyros	Ebenaceae	Ligneous	mp	GC-SZ
20	*Diospyros virginiana*	Diospyros	Ebenaceae	Ligneous	m_P	SZ
21	*Entada Africana* Guill. & Perr	Entada	Fabaceae	Ligneous	Lmp	SZ

22	*Gardenia ternifolia* Schum & Thonn	Gardenia	Rubiaceae	Ligneous	np	GC-SZ
23	*Hexalobus monopetalus* Engl. & Diels	Hexalobus	Anonaceae	Ligneous	mp	SZ
24	*Isoberlinia doka* Crai b.& Stapf.	Isoberlinia	Fabaceae	Ligneous	m_P	SZ
25	*Isoberlinia tomentosa* (Harms) Craib & Stapf	Isoberlinia	Fabaceae	Ligneous	m_P	SZ
26	*Lannea acida* Engl. &. Krause	Lannea	Anacardiaceae	Ligneous	mp	GC-SZ
27	*Lannea Barteri (Oliv.)* Engl.	Lannea	Anacardiaceae	Ligneous	mp	GC-SZ
28	*Lannea microcarpa* Engl. & K. Krause	Lannea	Anacardiaceae	Ligneous	mp	SZ
29	*Nauclea Latifolia* Sm.	Nauclea	Rubiaceae	Ligneous	mp	GC-SZ
30	*Parkia biglobosa* (Jcq.) R. Br. ex G. Don	Parkia	Fabaceae	Ligneous	mp	AT
31	*Piliostigma reticulatum* (DC.) Hochst.	Piliostigma	Fabaceae	Ligneous	np	GC-SZ
32	*Piliostigma thonningii*	Piliostigma	Fabaceae	Ligneous	np	GC-SZ
33	*Pterocarpus erinaceus* Poir.	Pterocarpus	Fabaceae	Ligneous	mp	SZ
34	*Sterculia setigera* Del.	Sterculia	Malvaceae	Ligneous	m_P	SZ
35	*Sterculia tragacantha* Lindl.	Sterculia	Malvaceae	Ligneous	m_P	SZ
36	*Tamarindus indica* L.	Tamarindus	Fabaceae	Ligneous	mp	GC-SZ
37	*Tectona grandis* L.f.	Tectona	Verbenaceae	Ligneous	M.P	i
38	*Terminalia albida Sc.* Elliot	Terminalia	Combretaceae	Ligneous	mp	SZ
39	*Terminalia avicennioides* Guill. & Per	Terminalia	Combretaceae	Ligneous	m_P	SZ
40	*Terminalia glaucescens* Planch. ex Benth.	Terminalia	Combretaceae	Ligneous	mp	SZ
41	*Vitellaria paradoxa* C.F.Gaertn	Vitellaria	Sapotaceae	Ligneous	mp	SZ
42	*Vitex doniana* Sweet	Vitex	Verbenaceae	Ligneous	mp	GC-SZ
43	*Zanthoxylum zanthoxyloides* (Lam.) Zepern. & Timler	Zanthoxylum	Rutaceae	Ligneous	mp	GC-SZ

44	*Ziziphus mauritiana*	Ziziphus	Rhamnaceae	Ligneous	mp	SZ

HERBACEOUS CHECKLIST

Number	Species	Genra	Family	Life form type	Chorological type
1	*Amaranthus hybridus* L.	Amaranthus	Amaranthaceae	Th	AT
2	*Aneilema* sp.	Aneilema	Commelinaceae	Ch	SZ
3	*Aristida verstingii*	Aristida	Poaceae	mp	SZ
4	*Arundinella pumila*	Arundinella	Poaceae	H	GC-SZ
5	*Aspilia africana* (Pers.) C.D. Adams.	Aspilia	Asteraceae	Th	SG
6	*Asystasia gangetica* (L.) T. Anders.	Asystasia	Acanthaceae	np	GC-SZ
7	*Boerhavia diffusa*	Boerhavia	Nyctaginaceae	Th	Cosmc
8	*Chloris pilosa* Schmach.	Chloris	Poaceae	Th	GC
9	*Cleome rutidosperma* DC.	Cleome	Cleomaceae	Th	GC
10	*Commelina* sp	Commelina	Commelinaceae	Ch	GC-SZ
11	*Corchorus aestuans*	Corchorus	Malvaceae	Th	GC-SZ
12	*Corchorus Olitorius*	Corchorus	Malvaceae	Th	GC-SZ
13	*Croton lobatus* L.	Croton	Euphorbiaceae	Th	GC-SZ
14	*Cynodon dactylon* (L.) Pers.	Cynodon	Poaceae	Ch	GC-SZ
15	*Cyperus rotundus*	Cyperus	Cyperaceae	H	GC-SZ
16	*Cyperus strigosus*	Cyperus	Cyperaceae	Ge	Pan
17	*Dactyloctenium aegyptium* (L.) P. Beauv.	Dactyloctenium	Poaceae	H	GC-SZ
18	*Desmodium scorpiurus* (Sw.) Desv.	Desmodium	Fabaceae	Ch	GC-SZ
19	*Digitaria sanguinalis* (L.) Scop.	Digitaria	Poaceae	np	AN
20	*Dissotis rotundifolia* (Sm.) Triana.	Dissotis	Herbaceous	Ch	GC-SZ
21	*Eclipta alba* (L.) L.	Eclipta	Asteraceae	Th	GC-SZ
22	*Eleusine indica* (L.) Gaertn.	Eleusine	Poaceae	Th	GC-SZ
23	*Eragrostis tenella* (L.) P Beauv.	Eragrostis	Poaceae	Th	GC-SZ
24	*Euphorbia hirta* L.	Euphorbia	Euphorbiaceae	Th	GC-SZ

25	*Hibiscus surattensis*	Hibiscus	Malvaceae	Ch	Pan
26	*Laportea aestuans* (L.) Chew.	Laportea	Urticaceae	Th	GC
27	*Leptocholoa chinensis* (L.) Nees.	Leptocholoa	Poaceae	H	Pan
28	*Luffa cylindrical* (L.) Roem.	Luffa	Cucurbitaceae	Lmp	i
29	*Malvastrum coromandelianum* (L.) Garcke.	Malvastrum	Malvaceae	np	GC
30	*Megathyrsus* maximus	Megathyrsus	Poaceae	H	GC
31	*Mimosa pudica* L.	Mimosa	Fabaceae	Th	i
32	*Momordica charantia* L.	Momordica	Cucurbitaceae	Lmp	GC-SZ
33	*Ocimum tenuiflorum*	Ocimum	Lamiaceae	np	Pal
34	*Oldenlandia corymbosa* L.	Oldenlandia	Rubiaceae	Th	GC-SZ
35	*Oxalis corniculata* L.	Oxalis	Oxalidaceae	Ch	GC
36	*Oxalis stricta* L.	Oxalis	Oxalidaceae	Ch	GC
37	*Panicum maximum*	Panicum	Poaceae	H	GC
38	*Paspalum scrobiculatum*	Paspalum	Poaceae	H	GC-SZ
39	*Pennisetum polystachion* (L.) Schult.	Pennisetum	Poaceae	Th	GC-SZ
40	*Pennisetum purpurreum*	Pennisetum	Poaceae	H	GC
41	*Phyllanthus amarus* Suhum & Thonn.	Phyllanthus	Euphorbiaceae	Th	GC
42	*Rottboellia cochinchinensis*	Rottboellia	Poaceae	Th	GC-SZ
43	*Sacciolepis africana* C.E. Hubbard & Snowden.	Sacciolepis	Poaceae	H	GC-SZ
44	*Setaria barbata* (Lam.) Kunth	Setaria	Poaceae	H	GC-SZ
45	*Sida acuta* Burm.F	Sida	Malvaceae	np	GC-SZ
46	*Spigella anthelmia* L.	Spigella	Loganiaceae	Th	AA
47	*Sporobulus pyramidalis*	Sporobulus	Poaceae	H	SZ
48	*Striga hermontrica*	Striga	Orobanchaceae	Par	SZ
49	*Stylosanthes Mucronata*	Stylosanthes	Fabaceae	Ch	GC-SZ
50	*Synedrella nodiflora* (L.) Gaertn.	Synedrella	Asteraceae	Th	GC-SZ
51	*Trianthema* sp. L.	Trianthema	Aizoaceae	Ch	GC-SZ

52	*Tridax procumbens* L.	Tridax	Asteraceae	Ch	GC-SZ
53	*Triumfetta dubia*	Triumfetta	Malvaceae	Ch	Pan
54	*Vernonia cinerea* (L.) Less	Vernonia	Asteraceae	np	GC-SZ
55	*Vetiveria nigritana*	Vetiveria	Poaceae	H	GC-SZ