REPUBLIQUE DE COTE D'IVOIRE
Union-Discipline-Travail

Ministère de l'Enseignement supérieur
et de la Recherche Scientifique

UNIVERSITE FELIX HOUPHOUET- BOIGNY

GRADUATE RESEARCH PROGRAMME: CLIMATE CHANGE AND BIODIVERSITY

Academic year: 2024-2025 Document number

THESIS

Submitted for the Degree of Doctor of Philosophy at University of Félix HOUPHOUËT-BOIGNY, Cocody-Abidjan

Speciality: Climate Change and Biodiversity

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Impact of Anthropogenic Activities and Soil Properties on Carbon Stocks, Woody Species Abundance and Conservation Status of Protected Areas within the Forest-Savannah Transition Zone of Ghana

Public defence on 27th June, 2025

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Spécialité : Changement Climatique et Biodiversité

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Impact des Activités Anthropiques et des Propriétés du Sol sur les Stocks de Carbone, L'abondance des Espèces Ligneuses et L'état de Conservation des Aires Protégées dans la Zone de Transition Forêt-Savane du Ghana

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Dedication

This thesis is dedicated to my parents, Noble Asibey Amankwah and Ernestina Anane-Oppong; my junior mother, Millicent Addai; and my sister, Nana Afua Akyaa Amankwah.

Acknowledgements

“For in Him we live, and move, and have our being”… I am deeply grateful to God for the gift of life and the countless blessings that have supported me on this journey. This thesis is the result of the support and efforts of many individuals and institutions, to whom I am sincerely thankful.

I extend my heartfelt appreciation to the German Federal Ministry of Education and Research (BMBF) for funding my doctoral studies, through the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL). I am also grateful to the faculty and staff of Université Félix Houphouët-Boigny (UFHB) in Abidjan, Côte d'Ivoire, and the University of Rostock, Germany, for hosting and supporting my research.

My sincere thanks go to my supervisors: Professor Edouard Kouassi (WASCAL, African Center of Excellence in Climate Change, Biodiversity & Sustainable Agriculture [CEA-CCBAD], Côte d'Ivoire), Professor Stephen Adu-Bredu (Forestry Research Institute of Ghana [FORIG]–Council for Scientific and Industrial Research [CSIR]), Professor Dr. Stefan Porembski (Institute of Biosciences, Department of Botany, University of Rostock, Germany) and Professor Jonathan Arthur Quaye-Ballard (Department of Geomatic Engineering, Kwame Nkrumah University of Science and Technology [KNUST]). Their dedication, support, and guidance have been invaluable throughout this journey.

I am incredibly thankful to the staff at the Forestry Research Institute of Ghana, particularly Mr. Emmanuel Amponsah Manu, Mr. Jonathan Dabor and Dr. Duah Gyamfi, for their assistance during data collection and analysis. I also extend my gratitude to the Wildlife Division of the Ghana Forestry Commission for their support in this research and their dedication to forest conservation. My heartfelt appreciation goes to the chiefs, management, staff and residents of Boabeng-Fiema Monkey Sanctuary and Kogyae Strict Nature Reserve for their warm welcome, support and cooperation.

I am deeply thankful to friends Bernard Eshun, Emmanuel Amoako and Kelvin Appiah-Badu, who provided encouragement and assistance during fieldwork. My gratitude also goes to Petra Kiehl, Katrin Stäuber, Dr. Nadja Biedinger, Luiz Bondi, Tabea Giese, Julius Köhler, Konrad Schultz, Elisabeth Zokov, Sir Sober Emmanuel, Mariam, Portia and Mary, whose kindness made my time in Rostock unforgettable.

I am grateful to my shepherds: Rev. Dr. Gospel and Benedette Odame Kentoe, Rev. Joseph and Mrs. Regina Turkson, Minister Richard Rocky and Alice Mireku-Debrah, Dennis Nii Sowah, Minister Stephen Donkor, Minister Francis Gyamfi, Minister Michael Adu-Kyereh, Minister Isaac Frimpong, Minister Prince Amfo and Mrs. Yaa Ohenewaa Boahene, for their unwavering guidance, encouragement and support.

I am grateful to my WASCAL colleagues for their companionship, support and motivation. A special mention goes to my coursemate, Colonel Michel Weblegnon Zrehon, for introducing us to the beauty of Abidjan and beyond. I extend my heartfelt gratitude to my friend Blessing Chinomso for her unwavering support and encouragement throughout this journey. I am thankful for my family, church family, friends, loved ones, and the warm-hearted people of Ghana, Côte d'Ivoire and Germany. To every one of you, I am genuinely grateful. Indeed, it takes a community to raise a doctoral graduate.

Abstract

Protected areas are fundamental for conserving biodiversity, yet they face increasing threats from human activities. This study assessed the impact of anthropogenic disturbance on carbon stocks, soil properties influencing woody species abundance, conservation status and local conservation practices in two protected areas in Ghana: Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR). Land Use and Land Cover Classes (LULCCs) were analysed using satellite imagery for 1992, 2010 and 2023, classifying landscapes into six categories. Tree inventory data were collected using a nested plot design and carbon stocks were estimated using allometric models and remote sensing. Soil samples (0-15 cm) were analysed for physicochemical properties, with eight properties retained for multivariate analysis. Canonical Correspondence Analysis (CCA) was used to evaluate the relationship between soil properties and woody species abundance. The conservation status was assessed using the Genetic Heat Index (GHI) and Red List Index (RLI). Community conservation data were gathered through questionnaires and analysed using SPSS. The results showed significant carbon losses due to anthropogenic activities: -40,236 Mg C in BFMS and -272,109 Mg C in KSNR. Soil properties explained 40.27% and 34.41% of species abundance variation in BFMS and KSNR, respectively. The conservation assessment showed high conservation value for BFMS (GHI = 134.24) and KSNR (GHI = 105.41). BFMS had an RLI of 0.21, while KSNR had a negative RLI (-1.55) due to the prevalence of *Pterocarpus erinaceus*, an endangered woody species. Key conservation strategies included wildfire protection in BFMS and increased staffing in KSNR. This study highlights the importance of nature-based solutions for climate change mitigation and biodiversity conservation, emphasising the need for enhanced protection measures.

Keywords: Biodiversity Conservation; Carbon sequestration; Genetic Heat Index; Nature-based Solution; Red List Index; REDD+

RÉSUMÉ

Les aires protégées sont essentielles à la conservation de la biodiversité, mais elles sont confrontées à des menaces croissantes liées aux activités humaines. Cette étude a évalué l'impact des perturbations anthropiques sur les stocks de carbone, les propriétés du sol influençant l'abondance des espèces ligneuses, l'état de conservation et les pratiques locales de conservation dans deux aires protégées du Ghana : le sanctuaire des singes de Boabeng-Fiema (BFMS) et la réserve naturelle intégrale de Kogyae (KSNR). Les classes d'utilisation et de couverture du sol (LULCC) ont été analysées à l'aide d'images satellite pour 1992, 2010 et 2023, classant les paysages en six catégories. Les données d'inventaire des arbres ont été collectées selon un plan d'échantillonnage en parcelles imbriquées et les stocks de carbone ont été estimés à l'aide de modèles allométriques et de télédétection. Des échantillons de sol (0-15 cm) ont été analysés pour leurs propriétés physico-chimiques, huit propriétés ayant été retenues pour une analyse multivariée. L'analyse canonique des correspondances (ACC) a été utilisée pour évaluer la relation entre les propriétés du sol et l'abondance des espèces ligneuses. L'état de conservation a été évalué à l'aide de l'indice de chaleur génétique (GHI) et de l'indice de la liste rouge (RLI). Français Les données de conservation communautaire ont été recueillies au moyen de questionnaires et analysées à l'aide de SPSS. Les résultats ont montré des pertes de carbone importantes dues aux activités anthropiques : -40,236 Mg C dans le BFMS et -272,109 Mg C dans le KSNR. Les propriétés du sol expliquaient respectivement 40.27 % et 34.41 % de la variation de l'abondance des espèces dans le BFMS et le KSNR. L'évaluation de la conservation a montré une valeur de conservation élevée pour le BFMS (GHI = 134.24) et le KSNR (GHI = 105.41). Le BFMS avait un RLI de 0.21, tandis que le KSNR avait un RLI négatif (-1.55) en raison de la prévalence de Pterocarpus erinaceus, une espèce ligneuse menacée. Les principales stratégies de conservation comprennent la protection contre les incendies de forêt dans le BFMS et l’augmentation du personnel dans le KSNR. Cette étude souligne l'importance des solutions fondées sur la nature pour l'atténuation du changement climatique et la conservation de la biodiversité, et insiste sur la nécessité de renforcer les mesures de protection

Mots-clés: Conservation de la biodiversité ; Séquestration du carbone ; Indice de chaleur génétique ; Solution fondée sur la nature ; Indice de la Liste Rouge ; REDD+

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List of Abbreviations

BFMS – Boabeng-Fiema Monkey Sanctuary

CBD – Convention on Biological Diversity

GHI – Genetic Heat Index

GDP - Gross Domestic Product

IUCN - International Union for Conservation of Nature

KSNR – Kogyae Strict Nature Reserve

LULCCs – Land Use Land Cover Classes

Nbs – Nature-Based Solution

PAs – Protected Areas

REDD – Reducing Emissions from Deforestation and Forest Degradation

REDD+ - Reducing Emissions through Deforestation and Forest Degradation (Conservation, sustainable management of forests and enhancement of forest carbon stock)

RLI – Red List Index

RS - Remote Sensing

SDG – Sustainable Development Goals

SFM - Sustainable Forest management

UAV - Unmanned Aerial Vehicle

UNFCCC - United Nation Framework Convention on Climate Change

UN FAO - United Nations Food and Agriculture Organization

WPAs – Wildlife-Protected Areas

CHAPTER 1

INTRODUCTION

1.1 Background

Protected areas (PAs) are key components in biodiversity conservation. These areas safeguard natural and cultural resources, support local livelihoods, maintain ecological processes across landscapes and promote sustainable development (Amankwah et al., 2024). In addition to biodiversity conservation, PAs contribute significantly to human welfare. Globally, approximately 1.1 billion people depend on protected areas for their livelihoods (Fuente et al., 2020). Furthermore, these areas serve as sources of drinking water for more than one-third of the world's largest cities and contribute to global food security (Dudley & Stolton, 2015). Protected areas within the forest-savannah transition zone support the ecological balance between forest and savannah ecosystems. The forest-savannah transition zone is an ecotone where forest and savannah ecosystems meet, found throughout the tropics. It serves as a habitat for diverse plant and animal species including endangered and rare species, making it instrumental in biodiversity conservation (Amankwah et al., 2021; Djagbletey et al., 2021). Biodiversity conservation improves the resistance and resilience of forest and savannah ecosystems to climate extremes and contributes to soil conservation (Chen et al., 2023; Isbell et al., 2015).

In Africa, the forest-savannah transition zone is an agricultural hub for many Sub-Saharan African countries (Amankwah et al., 2021). One notable example is the forest-savannah transition zone of Ghana, which extends through areas such as Kintampo, Wenchi, Techiman and Ejura and supports extensive crop production (Amankwah et al., 2021). Similarly, in Côte d'Ivoire, Nigeria and Cameroon, these transition zones play an important role in agriculture. Within these regions, cash crops such as cocoa and cashew are widely cultivated, benefiting from the combination of forest and savannah climatic conditions (Kadio et al., 2020; Owusu & Essandoh-Yeddu, 2018). As such, the transition zone not only supports livelihoods but also contributes to food security, gross domestic product (GDP) and socioeconomic development in Sub-Saharan African countries. Additionally, the transition zone functions as a global buffer zone and a key indicator of climate change (Stewart & Mallik, 2006). Ghana's forest area covers approximately 9.17 million hectares, which is about 40% of the country's total land area (Afele et al., 2022). These forests are classified into three primary ecological zones; the high forest zone, the transition zone and the savannah zone (Foli et al., 2021). Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR) are wildlife-protected areas in the forest-savannah transition zone of Ghana, with KSNR being the only strict nature reserve in the country (Afriyie et al., 2021b; Amankwah et al., 2021). Despite their ecological importance, anthropogenic activities such as illegal logging, poaching, farming and charcoal burning have been reported in both areas, leading to forest degradation and a decline in carbon stocks (Amankwah et al., 2021; Amankwah et al., 2024; Janssen et al., 2018; Singh et al., 2022). Furthermore, a major barrier to combating deforestation in Ghana is the exclusion of local communities from forest policy formulation, planning and implementation processes (Adusei & Dunyah, 2016). These challenges have necessitated further research to ensure their conservation.

There is increasing evidence that soil nutrients, including nitrogen, phosphorus, potassium, pH and magnesium, significantly influence woody species abundance and composition in the transition zone, accentuating the importance of understanding soil-vegetation interactions (Mensah et al., 2023; Sellan et al., 2019; Thammanu et al., 2021; Veríssimo et al., 2024). However, other factors such as climate variability (Zeng et al., 2014), topography (Saimun et al., 2021) and hydrology (Kreft et al., 2008; Yang et al., 2021) also play key roles in shaping woody species distribution and composition. Moreover, anthropogenic activities such as illegal felling of trees and charcoal burning have adversely impacted tropical forests, resulting in reduced carbon stocks, increased carbon dioxide emissions, biodiversity loss and an overall net loss of trees (Amankwah et al., 2021; Amankwah, et al., 2024). This highlights the urgent need for sustainable forest management (SFM) and conservation efforts. The study aimed to evaluate the influence of anthropogenic activities and soil properties on woody species composition and carbon stocks in BFMS and KSNR. It also sought to assess the conservation status of these protected areas and gather forest conservation practices from the perspectives of the local communities.

1.2 Problem Statement

Although Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR) are protected areas since 1970, there have been instances of anthropogenic disturbances, such as illegal logging, charcoal burning, encroachment and agricultural expansion. These activities have resulted in forest degradation, deforestation and a substantial reduction in carbon stocks (Afriyie et al., 2021c; Amankwah et al., 2021, 2024; Janssen et al., 2018). The resulting decline in forest productivity and ecosystem stability impairs the ability of these forests to provide important ecosystem services to the local communities (Ifo et al., 2016). Addressing these challenges is important for ensuring the long-term sustainability of these PAs and enhancing their capacity for biodiversity conservation and climate change mitigation.

1.3 Research Gaps

Although considerable research has been conducted on forest ecology, biodiversity conservation and carbon stocks, there remains a significant gap in comprehensive carbon stock estimation, particularly in the forest-savannah transition zone of Ghana (Adu-Poku et al., 2023). Most existing studies focus on either above-ground or soil carbon stocks, but few provide an integrated assessment that includes above-ground, belowground, herbs, litter, soil and deadwood (Adu-Poku et al., 2023; Djagbletey et al., 2018). Additionally, there is limited research on the influence of soil properties on woody species abundance and composition as well as the conservation status of forests and conservation practices from the perspective of local communities in Ghana. Furthermore, local communities are often excluded from policy formulation and forest management strategies due to poor communication, lack of collaboration and imposition of top-down policies (Afriyie et al., 2021a; Afriyie et al., 2021b; Ayivor & Ntiamoa-Baidu, 2015; Jachmann, 2008; Oduro-Ofori et al., 2015; Oduro et al., 2012). Given the growing emphasis on nature-based solutions, such as forests for climate change mitigation and adaptation, evaluating carbon stocks and conservation status, alongside insights from local communities are practical and effective strategies. This study addresses these knowledge gaps by providing integrated ecological and sociocultural insights into the SFM of Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR).

1.4 Justification

The forests of BFMS and KSNR are important for biodiversity conservation, carbon sequestration, local livelihoods and cultural and national heritage. However, increasing anthropogenic pressures threaten their sustainability (Amankwah et al., 2021; 2024). This study integrates ecological and socioeconomic factors to develop science-based conservation strategies. These strategies align with global sustainability frameworks, including the Sustainable Development Goals (SDGs), the Aichi Biodiversity Targets under the Convention on Biological Diversity (CBD) and findings from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Specifically, the study supports SDG 2 (Zero Hunger) by recognising the role of forests in food security and soil fertility for sustainable agriculture. It aligns with SDG 11 (Sustainable Cities and Communities) by evaluating forest practices to promote sustainable land-use planning and forest management. The study contributes to SDG 13 (Climate Action) by assessing carbon stocks in BFMS and KSNR to inform climate adaptation strategies. Additionally, it addresses SDG 15 (Life on Land) by analysing the influence of soil properties on woody species composition.

In alignment with the Aichi Biodiversity Targets (UN-REDD, 2012), the study addresses Target 5 (Reducing Habitat Loss) by assessing the extent of deforestation and land degradation. It supports Target 7 (Sustainable Forest Management) by promoting responsible land-use practices. The research contributes to Target 11 (Protected Areas Conservation) by evaluating the conservation status of BFMS and KSNR. It also aligns with Target 14 (Ecosystem Services and Livelihoods) by integrating local community perspectives. Finally, the study advances Target 15 (Ecosystem Restoration and Climate Resilience) by assessing carbon sequestration potential and forest resilience.

Furthermore, the study reinforces key IPBES reports. The 2019 Global Assessment on Biodiversity and Ecosystem Services highlights deforestation as a major driver of biodiversity loss (IPBES, 2019). The 2018 Regional Assessment for Africa emphasizes the importance of community-led conservation (IPBES, 2018). The IPBES-IPCC Joint Report links biodiversity conservation to climate change mitigation. By integrating these global frameworks, this study provides a comprehensive approach to sustainable forest management, ensuring that BFMS and KSNR continue to function as important ecosystems for biodiversity, climate resilience, and sustainable livelihoods.

1.5 Research Aim and Objectives

The study aimed to assess the impact of human-induced disturbances and soil properties on carbon dynamics and woody species composition in protected areas of the forest-savannah transition zone in Ghana. Additionally, it evaluated the conservation status of these ecosystems and incorporated local community perspectives on forest management and protection efforts.

The formulated specific objectives are:

1. To assess the effects of anthropogenic activities on carbon stocks in BFMS and KSNR;
2. To determine the influence of soil properties on woody species abundance in BFMS and KSNR;
3. To evaluate the conservation status of BFMS and KSNR;
4. To assess forest conservation practices in BFMS and KSNR from the perspectives of the local population.

1.6 Research Questions

The formulated questions in addressing the above specific objectives are:

1. What are the effects of anthropogenic activities on carbon stocks in BFMS and KSNR?
2. How do soil properties influence woody species abundance in BFMS and KSNR?
3. What is the conservation status of BFMS and KSNR?
4. What insights can be drawn from forest conservation practices from the perspectives of the local communities surrounding BFMS and KSNR?

1.7 Hypotheses

The formulated hypotheses in addressing the above specific objectives are:

1. Anthropogenic activities negatively affect the carbon stocks of BFMS and KSNR, leading to a reduction in carbon sequestration, carbon stock and forest degradation;
2. Soil properties in BFMS and KSNR influence the abundance of woody species, thereby affecting forest resilience and ecological health;
3. The conservation status assessment of BFMS and KSNR, based on bioquality indices, reflects the distribution of rare, endemic and threatened woody species, providing insights for conservation planning;
4. The conservation practices from the perspectives of local communities in BFMS and KSNR, will make a substantial contribution to the protection and sustainability of the protected areas.

1.8 Organisation of Thesis

The thesis is organised into five distinct chapters to ensure a coherent and structured presentation of the research.

- **Chapter 1: Introduction**

  This chapter introduces the study, outlining the background and problem statement. It identifies the research gaps and justifies the research. The chapter also covers the research aim, objectives, research questions and hypotheses, establishing the foundation for investigation.

- **Chapter 2: Literature Review**

  Chapter 2 provides a theoretical framework and places the study within the broader academic discourse. The literature review explores key topics, including the importance of protected areas, the ecological and socio-economic significance of the forest-savannah transition zone and the role of this zone in carbon sequestration. Additionally, it explores protected areas as nature-based solutions (Nbs) for ecosystem restoration and climate resilience. It further explores the potential of this zone for climate change mitigation, adaptation and resilience. The chapter also evaluates stakeholder engagement, challenges faced in protected areas, anthropogenic pressures in the transition zone and the role of soil in shaping wooding species composition within the zone. The chapter also reviews carbon finance mechanisms such as the Clean Development Mechanism (CDM) under the Kyoto Protocol, assessing how protected areas and the transition contribute to carbon-offset programmes. It also examines the methodological advancements in forest management, particularly the use of GIS and remote sensing for ecosystem monitoring, which serve as essential tools for conservation planning and sustainable resource management. The chapter concludes with an assessment of the conservation status of forest ecosystems, focusing on various approaches and indicators, including species rarity, extinction risk and biodiversity metrics, to provide a comprehensive understanding of forest conservation priorities.

- **Chapter 3: Material and Methods**

  This chapter outlines the research methods and processes, including data collection and analysis techniques employed in this research. It details the procedures for mapping, carbon stock evaluation, assessment of soil properties and the administration of questionnaires to gather relevant data.

- **Chapter 4: Results and Discussion**

Chapter 4 presents the research findings and provides a detailed discussion of the results of the study objectives. The chapter begins with an analysis of woody species composition, highlighting species diversity, richness and distribution patterns across the study sites. It further identifies species with high Importance Value Index (IVI), emphasising dominant tree species that play important ecological roles in the forest-savannah transition zone. The chapter also examines carbon stocks across different pools, including aboveground biomass, belowground biomass, herbs, litter and soil organic carbon. It evaluates the carbon density variations among the land use land cover classes (LULCC) and discusses the implications of carbon storage capacity in the transition zone for climate change mitigation. Additionally, the chapter presents findings on soil physicochemical properties, such as pH, nitrogen, bulk density, phosphorus and potassium, and which soil properties influence woody species composition, using statistical models to establish relationships between soil characteristics and vegetation structure. Furthermore, the chapter evaluates the conservation status of protected areas, identifying species that are rare, threatened and of high ecological significance based on global and regional conservation assessments. It also explores forest conservation practices adopted by local communities within the protected areas. The discussion integrates these findings with existing literature within Africa and globally, providing insights into how protected areas function as nature-based solutions for biodiversity conservation, carbon sequestration and ecosystem resilience.

- **Chapter 5: Conclusions and Recommendations**

  The final chapter summarizes the key outcomes of the research, addresses the limitations of the study and offers recommendations for future research areas.

CHAPTER 2

LITERATURE REVIEW

2.1 Protected Areas

The International Union for Conservation of Nature (IUCN) defines a protected area as "an area of land and/or sea especially dedicated to the protection and maintenance of biological diversity and natural and associated cultural resources and managed through legal or other effective means". This definition is further categorised into six main types (Dudley, 2008):

1. Strict nature reserve (1a): These areas are strictly protected to conserve biodiversity, as well as geological or geomorphological features. Human access, use and impacts are highly restricted to ensure the preservation of their conservation values.

- Wilderness area (1b): They are typically large unmodified or slightly modified areas that retain their natural character and ecological processes without permanent or significant human habitation. These areas are protected and managed to preserve their pristine condition.

2. National park (II): These are extensive natural or near-natural areas designated to protect large-scale ecological processes, species and ecosystems. They also provide environmentally and culturally compatible opportunities for spiritual, scientific, educational and recreational activities along with controlled visitor access.
3. Natural monument or feature (III): These areas are designated to protect specific natural monuments, which may include seamounts, marine caverns, landforms, geological features such as caves, or living features such as ancient groves.
4. Habitat/species management area (IV): These areas are managed primarily for the conservation of specific species or habitats. Many of these areas need regular and ongoing interventions to support targeted species or habitat needs, though this is not a mandatory criterion for classification.
5. Protected landscape or seascape (V): These areas have been shaped by long-term interactions between people and nature, resulting in distinct biological, cultural, ecological and scenic value. Maintaining the integrity of this interaction is essential for sustaining the areas' conservation values and overall ecological balance.
6. Protected areas with sustainable use of natural resources (VI): These areas integrate ecosystem conservation with traditional natural resource management practices and cultural values. They are generally large and predominantly in a natural state with a

proportion under sustainable resource use. Low-impact, non-industrial resource extraction is permitted, provided it aligns with conservation objectives.

The designation and expansion of protected and conserved areas remain key strategies for biodiversity conservation and ecosystem resilience, particularly in response to anthropogenic pressures and climate change. According to the Protected Planet (2024) report, the global coverage of protected and conserved areas has now reached 17.6% of terrestrial and inland waters and 8.4% of marine and coastal areas. This progress reflects the commitment of nations and international organizations to meeting global conservation targets. For instance, under the Post-2020 Global Biodiversity Framework, the Convention on Biological Diversity (CBD) has established Target 3, which seeks to conserve 30% of terrestrial, inland water, and marine and coastal areas by 2030 (30x30 target). These designations align with global conservation targets such as the Aichi Biodiversity Targets and the Kunming-Montreal Global Biodiversity Framework, which aim to expand and enhance the effectiveness of protected areas (Ekardt et al., 2023; Friedman et al., 2022). Achieving these goals requires not only expanding the coverage of protected areas but also ensuring their ecological representativeness, effective governance, and sustainable management.

The subsequent headings will explore the importance of protected areas, emphasizing their role in biodiversity conservation and ecosystem services, including habitat protection, species preservation, and ecological stability. It will examine their contribution to climate change mitigation and adaptation, particularly as carbon sinks that regulate global carbon balance. Additionally, the socioeconomic contributions of protected areas, such as their support for livelihoods through ecotourism, employment, and cultural heritage preservation, will be discussed. The review will also assess anthropogenic pressures and their impact on protected areas, highlighting threats like deforestation, agricultural expansion, and illegal resource extraction. Key topics include an overview of protected areas in Ghana, the role of protected areas in nature-based solutions and climate resilience, and the ecological and socioeconomic significance of the forest-savannah transition zone. An important aspect of the review will be the forest-savannah transition zone, examining its ecological and socioeconomic importance, as well as its role in carbon sequestration, climate change mitigation and adaptation. The influence of soil properties in shaping vegetation and ecosystem functionality in tropical forests and transition zones will also be explored. A key focus will be on the vegetation dynamics of BFMS and KSNR, analysing shifts in forest structure, species composition, and land-use changes over time. Furthermore, the review will explore the Clean Development Mechanism (CDM) under the Kyoto Protocol and carbon finance, assessing how protected areas contribute to carbon offset programs. Advancements in forest management methodologies, including GIS and remote sensing for ecosystem monitoring, will be examined as essential tools for conservation planning and sustainable resource management. Finally, the assessment of the conservation status of forest ecosystems will be explored, focusing on quantitative approaches to evaluate species rarity, extinction risk and biodiversity significance, thereby informing conservation priorities and management strategies.

2.1.1 Importance of Protected Areas

Protected areas (PAs) play a major role in biodiversity conservation, climate change mitigation, and the socio-economic well-being of adjacent communities. These designated spaces serve as refuges for a wide range of flora and fauna, many of which cannot thrive in intensively managed landscapes or seascapes (Singh et al., 2022). The establishment and effective management of PAs are fundamental for maintaining ecological balance, protecting endangered species and contributing to global biodiversity conservation targets (Mohammed et al., 2021).

2.1.1.1 Biodiversity Conservation and Ecosystem Services

PAs play a key role in biodiversity conservation by safeguarding genetic diversity and maintaining ecosystem services that support both ecological integrity and human well-being. These services, which include water purification, air quality regulation, soil fertility maintenance and climate regulation, are fundamental to sustaining life on earth (Daněk et al., 2023). As natural reservoirs of biodiversity, PAs serve as habitats for a wide range of species, including endemic and threatened taxa, many of which require undisturbed habitats for their survival (Tchaleu et al., 2024). The preservation of such areas ensures the continued existence of species that might otherwise face extinction due to habitat degradation, deforestation, and anthropogenic pressures

Beyond species protection, PAs also function as critical ecological corridors that facilitate species migration and gene flow. These movement pathways enable species to navigate between habitats in response to seasonal variations, resource availability and shifting climatic conditions (Cardoso et al., 2021; Schilthuizen, 2000). This connectivity is particularly vital in the face of climate change, where shifting temperature and precipitation patterns can alter habitat suitability and force species to relocate to maintain viable populations. Without such corridors, habitat fragmentation could isolate populations, leading to reduced genetic diversity and an increased risk of local extinctions.

Furthermore, PAs contribute significantly to ecosystem stability by buffering against environmental disturbances and mitigating the impacts of extreme weather events (Cardoso et al., 2021). Forested PAs, for example, enhance regional hydrological cycles by regulating water flow, reducing flood risks, and preventing soil erosion (Boakye et al., 2017). Similarly, wetland PAs act as natural water filtration systems, improving water quality by trapping sediments and pollutants before they reach freshwater sources (Roriz et al., 2017). These functions underscore the broader ecological and socioeconomic importance of PAs, as they provide essential services that benefit not only wildlife but also local communities that depend on them for resources, agriculture and cultural values.

2.1.1.2 Climate Change Mitigation and Adaptation

One of the most significant contributions of PAs to global environmental health is their role in mitigating climate change (Singh et al., 2022). As natural carbon sinks, forested PAs sequester atmospheric carbon dioxide (CO_2), thereby reducing greenhouse gas concentrations and mitigating global warming (Amankwah, et al., 2024). In West Africa, the Atewa Range Forest Reserve and Kakum National Park in Ghana serve as important carbon sinks, with their dense tree cover and rich biodiversity contributing to long-term carbon storage (Tsai et al., 2019). Similarly, tropical rainforests in Côte d’Ivoire Comoe National Park and Nigeria Cross River National Park store significant amounts of carbon while supporting a wide array of endemic and endangered species (Ahenkan, 2014; Goetze et al., 2006).

Beyond forests, other ecosystems within PAs, including mangroves, wetlands and peatlands, store substantial amounts of carbon in their biomass and soil, making them essential for climate regulation (Maure et al., 2023). Coastal mangrove forests in Ghana’s Amanzule Wetlands and Nigeria’s Niger Delta capture and store carbon at rates higher than most terrestrial forests while also protecting coastal communities from storm surges and sea-level rise (Adotey et al., 2022). Peatlands, such as those found in the Congo Basin, store carbon accumulated over thousands of years, preventing its release into the atmosphere (Rees et al., 2023). However, these ecosystems are highly vulnerable to degradation from agricultural expansion, logging and infrastructure development, which could result in substantial carbon emissions if not properly managed (Saimun et al., 2021).

In addition to carbon sequestration, PAs contribute to climate adaptation by preserving intact ecosystems that enhance resilience against climate change impacts. Healthy forest ecosystems regulate local microclimates, reduce surface temperatures and maintain humidity levels, helping to buffer against extreme heat events and droughts (Isbell et al., 2015). For instance, the Mole National Park in Ghana and W-Arly-Pendjari (WAP) National Park spanning Niger, Burkina Faso, and Benin help stabilise regional climate conditions by preventing further land degradation in the Sahel region (Harris et al., 2019). Wetlands such as Ghana's Songor Lagoon and Côte d'Ivoire's Azagny National Park act as natural flood control systems, absorbing excess water during heavy rainfall and mitigating the risk of flooding in nearby communities (N'dohou et al., 2023). Grasslands and savannah ecosystems within PAs, such as Ghana's Digya National Park and Burkina Faso's Arly National Park, prevent desertification by stabilising soils and maintaining vegetation cover in arid and semi-arid regions (Harris et al., 2019).

Furthermore, by maintaining biodiversity and ecosystem integrity, PAs support species adaptation to shifting climatic conditions. They provide important habitats and migration corridors that allow wildlife to move in response to changing environmental conditions. This is particularly important for species with specific temperature and precipitation requirements, such as migratory birds in the Ramsar-designated wetlands of Ghana and elephant populations in transboundary parks like the W-Arly-Pendjari Complex (Harris et al., 2019; Oduro et al., 2012).

2.1.1.3 Socioeconomic Contributions: Livelihoods and Cultural Benefits

Beyond their ecological significance, PAs contribute substantially to local, national and global economies. Approximately 1.1 billion people worldwide rely on protected areas for their livelihoods, particularly in rural communities where natural resources form the basis of economic sustenance (Fuente et al., 2020; Naughton-Treves et al., 2005). These areas support multiple economic activities, including small-scale agriculture, sustainable forestry, fisheries and harvesting of non-timber forest products (NTFPs) such as medicinal plants, wild fruits, honey and rattan, which serve as key sources of income and food security for local populations.

In Africa, Ankasa Conservation Area in Ghana and Taï National Park in Cote d'Ivoire provide essential resources for traditional medicine and craft industries (Kpan, 2022). Similarly, in the Amazon rainforest, indigenous communities depend on forest resources such as Brazil nuts, acai berries, and medicinal plants, which are integral to their subsistence economy and are also traded globally (Borma et al., 2022). In Southeast Asia, communities around Indonesia's Leuser Ecosystem sustainably harvest wild honey, rattan, and medicinal plants, balancing conservation with livelihood needs (Nugroho et al., 2022).

In addition to resource-based livelihoods, ecotourism within PAs provides employment opportunities, stimulates local businesses, and generates revenue for conservation initiatives (Eshun & Tonto, 2014). In Africa, Kenya's Maasai Mara and Tanzania's Serengeti attract thousands of tourists annually, generating millions of dollars in revenue that supports conservation and local communities (Kija et al., 2020; Weldemichel & Lein, 2019). Across the Americas, Yellowstone National Park in the United States attracts millions of tourists generating income for local economic benefits through ecotourism, accommodation, and recreational activities such as wildlife viewing and hiking (Keiter, 2020). Similarly, in Latin America, Costa Rica's Monteverde Cloud Forest Reserve attracts international tourists, generating funds that contribute to conservation, research, and community projects (Newcomer et al., 2022). In Europe, national parks such as the Dolomites in Italy and Plitvice Lakes in Croatia play a crucial role in rural economies by supporting businesses in hospitality, guiding services, and adventure tourism (Garasic & Garasic, 2021).

Beyond economic benefits, PAs also play a fundamental role in cultural and spiritual well-being, particularly for indigenous and local communities that have historical and spiritual ties to these landscapes (Amankwah et al., 2021; Kankam et al., 2013; Subashree et al., 2021). Many sacred forests and culturally significant sites are located within PAs, serving as places for traditional ceremonies, rites of passage and ancestral worship. In Ghana, the Boabeng-Fiema Monkey Sanctuary is deeply embedded in local traditions, where the Mona and Colobus monkeys are considered sacred and protected by cultural taboos (Kankam et al., 2013). In India, the Khasi and Garo communities in Meghalaya maintain sacred groves, which are biodiversity hotspots that serve both ecological and spiritual purposes (Upadhyay et al., 2019). Similarly, Australia's Uluru-Kata

Tjuta National Park holds deep spiritual significance for the Anangu people, and its management incorporates indigenous knowledge and cultural traditions (Walliss, 2016).

2.1.2 Anthropogenic Pressures and their Impact on Protected Areas

Protected areas (PAs) serve as mainstays for biodiversity conservation and ecosystem stability. However, they are increasingly threatened by anthropogenic pressures, which undermine their ecological integrity and long-term sustainability (Saimun et al., 2021). Human activities such as habitat destruction, illegal resource extraction, climate change, invasive species introduction, unsustainable tourism, human-wildlife conflict, pollution and weak governance all pose significant challenges to the effectiveness of PAs in preserving biodiversity and ecosystem services (Ayivor et al., 2020; Janssen et al., 2018). These pressures, if not adequately addressed, could lead to severe environmental consequences and compromise conservation efforts globally.

One of the most prominent threats to PAs is habitat destruction and land use change. Agricultural expansion, urbanisation, and infrastructure development encroach on protected landscapes, leading to habitat fragmentation and biodiversity loss (Da Ponte et al., 2017). For example, the Amazon rainforest, home to numerous PAs, faces extensive deforestation due to cattle ranching and soy farming (Valencia et al., 2024). Such land use changes not only reduce habitat availability for wildlife but also disrupt ecological processes, such as carbon sequestration and hydrological cycles, which are essential for climate regulation.

Illegal resource extraction, including poaching, logging, and mining, further exacerbates the degradation of PAs (Ayivor & Ntiamoa-Baidu, 2015). These activities deplete important resources, threaten key species and lead to habitat destruction. In Peru's Tambopata National Reserve, for instance, illegal gold mining has resulted in severe deforestation and mercury pollution, posing significant risks to both biodiversity and local communities (Oliveras et al., 2020). The lack of effective monitoring and enforcement mechanisms allows such activities to persist, further challenging conservation efforts.

Human-wildlife conflict arises when human settlements are established near PAs, increasing interactions between people and wildlife. Species such as elephants and large carnivores frequently raid crops and prey on livestock, leading to economic losses for local communities and retaliatory killings of wildlife (Y. Zeng et al., 2023). In Jim Corbett National Park, India, tigers and leopards often prey on livestock, which has led to conflicts between local communities and conservation authorities (Kumar et al., 2019; Mir et al., 2023). Mitigation strategies such as compensation schemes, buffer zones and community-based conservation programs are crucial in addressing these conflicts.

Pollution and environmental degradation are additional threats to PAs, originating from industrial activities, agricultural runoff and waste disposal. Marine protected areas (MPAs), such as the Great Barrier Reef, have suffered from coral bleaching and ecosystem degradation due to climate change-induced ocean warming and pollution from human activities (Lucrezi et al., 2019; Wang & Gu, 2021). Effective pollution control measures and sustainable land-use practices are necessary to reduce environmental contamination in PAs.

Addressing anthropogenic pressures on PAs requires a multi-faceted approach that integrates policy interventions, scientific research, community participation and sustainable management practices. Enhancing law enforcement, promoting conservation education and developing alternative livelihoods for local communities can contribute to reducing human-induced threats and ensuring the sustainability of PAs. By recognising and mitigating these pressures, conservation efforts can be more effective in safeguarding biodiversity and ecosystem services within protected areas worldwide.

2.1.3 Nature-Based Solutions and Climate Resilience

Nature-based solutions (NbS) offer a holistic and sustainable approach to conservation by leveraging natural ecosystems to address environmental challenges such as climate change, biodiversity loss and water security (Malhi et al., 2020). According to the International Union for Conservation of Nature (IUCN) and the World Wide Fund for Nature (WWF), NbS are actions that protect, sustainably manage and restore natural and modified ecosystems to benefit both people and nature. These solutions target major societal challenges, including climate change adaptation and mitigation, disaster risk reduction, food and water security, biodiversity conservation and human health.

Protected and conserved areas are Nbs as they play a fundamental role in enhancing ecosystem resilience, mitigating climate impacts and supporting local livelihoods (Amankwah et al., 2024). By working with nature rather than against it, protected areas provide cost-effective and adaptable strategies that benefit both people and the environment. Climate change poses severe threats to biodiversity and ecosystem stability, with rising temperatures, extreme weather events and habitat degradation disrupting natural processes (Roriz et al., 2017). However, PAs and conserved areas provide a vital response to these challenges through their ability to sequester carbon, regulate water cycles and reduce disaster risks. For example, mangrove forests act as natural storm barriers, protecting coastal communities from storm surges and sea-level rise, while restoring degraded watersheds and riparian forests in flood-prone areas reducing the impact of heavy rainfall and preventing soil erosion (Adotey et al., 2022). Coastal regions such as the Amanzule mangrove in Ghana and Nigeria's Niger Delta act as natural storm barriers, protecting communities from storm surges while providing essential breeding grounds for fish (Adotey et al., 2022; Numbere & Camilo, 2018). Coral reef restoration in Seychelles has improved coastal resilience by reducing wave energy and protecting shorelines from erosion (Maya et al., 2016). Furthermore, these ecosystems store significant amounts of carbon in their soils and biomass, offering a natural solution for reducing greenhouse gas emissions. Donato et al. (2011) corroborated that mangroves are amongst the most carbon-rich ecosystems.

Ecosystem restoration strengthens natural defences against climate change and reduces the risks of climate-related disasters such as floods, droughts, and wildfires. Restoring wetlands helps buffer communities from flooding by absorbing excess water, while conserving salt marshes and coral reefs mitigates coastal erosion and storm damage (Gray et al., 2018). Similarly, reforestation efforts in the Mau Forest Complex in Kenya have restored water catchment services, ensuring water availability for agriculture and hydropower (Chepkemoi & Musya, 2023). Tropical forests, such as the Amazon, Congo Basin, and Ghana's Atewa Range, act as carbon sinks by absorbing large amounts of CO_2 from the atmosphere (Amponsah et al., 2022; Rees et al., 2023; Veríssimo et al., 2024). In arid and semi-arid regions, like the Sahel, grassland restoration, enhances soil fertility and prevents desertification, enabling communities to adapt to shifting climatic conditions (Klein et al., 2015).

Governments and conservation organisations worldwide are integrating NbS into climate policies and protected area management. Europe's Green Infrastructure Strategy promotes NbS to enhance biodiversity, improve urban resilience, and strengthen ecosystem connectivity (Chatzimentor et al., 2020; Hermoso et al., 2020). China's Sponge Cities Initiative incorporates wetlands, green roofs, and permeable landscapes to reduce urban flooding and improve water management (Song, 2022). In Africa, South Africa's Working for Water Program employs local communities to remove invasive species that threaten biodiversity and deplete water resources (Binns et al., 2001; Stafford et al., 2017). Similarly, Costa Rica's Payment for Ecosystem Services (PES) Model incentivises landowners to maintain forests, contributing to both carbon sequestration and biodiversity conservation (Brownson et al., 2020). NbS must be people-centred and inclusive, drawing from traditional and local knowledge. Indigenous peoples and local communities have implemented NbS for millennia, relying on ecosystem-based approaches for food security, water management and climate resilience (Constant & Taylor, 2020).

For protected areas to remain effective in a changing climate, NbS must be integrated into management strategies. Strengthening ecosystem-based adaptation approaches ensures that biodiversity conservation aligns with climate resilience goals. Engaging local communities in sustainable resource management recognises their role as stewards of conservation landscapes. Promoting policy frameworks that support NbS investments secures funding for restoration projects, carbon offset programs, and community-driven conservation initiatives. By prioritising nature-based solutions, protected areas can become more resilient to climate change, provide long-term environmental and economic benefits, and enhance the well-being of local communities. A holistic approach that combines scientific research, traditional knowledge, and innovative governance models is essential for achieving sustainable and equitable conservation outcomes in the face of global climate challenges.

2.1.4 Stakeholder Engagement and Challenges in the Management of Protected Areas

Protected areas (PAs) are a fundamental strategy for biodiversity conservation. However, their management faces numerous challenges, including the lack of involvement of all stakeholders in conservation efforts and policy-making, policies that do not favour local communities, resource exploitation by the local population and insufficient funding (Ayivor et al., 2020). These challenges are not confined to a single region but are a global concern. For instance, in the Qinghai–Tibet Plateau, China, some rural communities within protected areas remained pessimistic about conservation due to a decline in the benefits of recreational ecosystem services. This decline results from restrictive policies that limit access to natural resources thereby reducing opportunities for ecotourism, cultural practices and nature-based livelihoods (Zeng et al., 2023). Consequently, these restrictions have led to economic vulnerability and socio-cultural discontent. This shift in perception underscores the unintended socio-economic consequences of conservation efforts that fail to integrate local livelihoods. Addressing these challenges requires inclusive conservation strategies that ensure equitable distribution of recreational ecosystem services benefits while maintaining ecological integrity.

Lucrezi et al. (2019) examined the bilateral nature of stakeholder engagement in managing marine protected areas in southern Mozambique. They emphasized both stakeholder empowerment and the influence of stakeholder input on management strategies. The research highlighted how ocean literacy, marine education and environmental monitoring initiatives shape stakeholder perspectives on conservation, community engagement and livelihoods. Through focus group discussions conducted before and after participation in these initiatives, the study demonstrated that stakeholder views evolved, with some aligning more closely with conservation goals. In contrast, others raised critical management challenges that required attention.

Husseini et al. (2020) corroborated these findings, emphasising that local communities in Northern Ghana often lack adequate knowledge of their rights and responsibilities concerning forest reserves. This knowledge gap limits their ability to actively participate in conservation efforts, leading to misunderstandings, conflicts over resource use and reduced community engagement in sustainable forest management. The study highlighted that the exclusion of local populations from decision-making processes not only weakens conservation outcomes but also exacerbates socio-economic vulnerabilities, as these communities depend on forest resources for their livelihoods. To address these challenges, Husseini et al. (2020) recommended fostering greater community involvement in forest governance through participatory management approaches, environmental education programs, and transparent policy frameworks that recognise and integrate local ecological knowledge. Strengthening collaboration between governmental agencies, conservation organisations and local communities is essential to ensuring equitable resource access, enhancing forest stewardship and promoting long-term sustainability.

Oduro-Ofori et al. (2015) identified structural conflicts as a major challenge in managing Ghana's only strict nature reserve. These conflicts stem primarily from weak law enforcement and top-down policy implementation without adequate stakeholder participation. This often leads to resistance from local communities, who feel excluded from decision-making processes that directly impact their livelihoods and access to resources. Similarly, Afriyie et al. (2021c) noted that the lack of effective communication and collaboration among community members within the strict nature reserve in Ghana hinders sustainable forest management. The absence of structured dialogue between local stakeholders, conservation authorities and policymakers weakens efforts to promote community-led conservation initiatives, leading to non-compliance with regulations, resource-use conflicts and reduced support for conservation policies. Addressing these issues requires a participatory governance approach that integrates local knowledge, fosters collaboration and strengthens law enforcement to ensure equitable and sustainable forest management in the reserves.

Adusei & Dunyah (2016) assessed local community participation in the sustainability of the Tain I Forest Reserve in Ghana, revealing that despite the existence of a management plan, its implementation remained inadequate and community involvement was minimal. This lack of engagement has hindered effective conservation efforts and long-term sustainability. Their findings align with those of Ayivor & Ntiamoa-Baidu (2015), who studied socioeconomic stressors affecting the KSNR. They emphasised that stakeholder participation is key in preserving the ecological integrity of KSNR, recognising that conservation efforts cannot succeed without active local involvement. Similarly, Afriyie et al. (2021c) advocated for the integration of local ecological knowledge into the management of KSNR, arguing that the traditional ecological knowledge of local inhabitants can enhance conservation outcomes. Collectively, these studies underscore the necessity of inclusive and participatory management approaches to ensure the sustainable protection of Ghana's forest reserves.

Toktarova et al. (2022) provided a global perspective on the challenges of PA management globally, underscoring the key role of stakeholder involvement in decision-making and the influence of public attitudes and perceptions on PA success. Their study identified uncontrolled human activities (such as hunting, poaching, and fishing) and unsustainable tourism development as major threats to achieving conservation objectives. To promote the effectiveness of the management of PA, it is essential to develop integrated strategies that address these multiple challenges while guiding the design and implementation of new environmental policies.

Collectively, these studies highlight the importance of involving local communities in managing protected areas to achieve effective conservation outcomes. However, there is limited research on forest conservation practices specific to these communities and even fewer studies focus on fringe communities within protected areas. This research addresses this gap by exploring forest conservation practices from the perspective of local communities within protected areas.

2.2 Overview of Protected Areas in Ghana

The conservation and protection of forest and wildlife resources in Ghana date back to 1906 with the establishment of the Forestry Department, now known as the Forestry Commission (FC). The Forestry Commission regulates, conserves and manages forest and wildlife resources while coordinating related policies. Its operations are structured under five Divisions; the Forest Services Division, Wildlife Division, Timber Industry Development Division, Forestry Commission Training Center and Resource Management. Over the years, Ghana implemented forest policies in 1948, 1994 and 2012, introducing measures to promote the sustainable management of forest and wildlife resources. These policies included the establishment of permanent forest estates, the enhancement and management of forest and wildlife resources and the involvement of rural communities in conservation efforts. Additional objectives include increasing biodiversity conservation, promoting the sustainable management of savannah woodlands, improving research and application of modern and scientific technology in resource management, developing climate change mitigation measures and integrating local conservation practices into national strategies.

The forests of Ghana are categorised into three main types; on-reserve forests, off-reserve forests and protected areas (PAs). The country has 282 PAs covering a total area of 22,754 km^2 (Ministry of Lands and Natural Resources, 2012). The Wildlife Division of the Forestry Commission manages wildlife protected areas (WPAs), which include seven National parks, six Resources Reserves, four Wildlife Sanctuaries, one Strict National Reserve and five Coastal Wetlands, designated as Ramsar Sites of which BFMS and KSNR are part (Table 2.1, Oduro et al. 2012).

Table 2.1: Wildlife protected areas in Ghana (Oduro, 2012)**.**

	Protected Areas
National Parks	Bia National Park & Resource Reserve
	Bui National Park
	Digya National Park
	Gbele National Park
	Kakum National Park
	Kyabobo National Park
	Mole National Park
Resource Reserves	Ankasa and Nini-Suhyen Forest Reserve
	Assin Atandanso Resource Reserve
	Bia Resource Reserve
	Gbele Resource reserve
	Kalakpa Resource Reserve
	Shai Hills Resource Reserve
Wildlife Sanctuaries	Owabi Wildlife Sanctuary
	Bomfobiri Wildlife Sanctuary
	Boabeng Fiema Monkey Sanctuary
	Agumatsa Wildlife Sanctuary
Strict Nature Reserve	Kogyae Strict Nature Reserve
Coastal Wetlands	Songor Ramsar Site
	Anlo-Keta Ramsar Site
	Sakumo Ramsar Site
	Densu Delta Ramsar Site
	Muni-Pomadze Ramsar Site

2.3 The Forest-Savannah Transition Zone

The forest-savannah transition zone (FSTZ) represents an ecotone between forest and savannah ecosystems, characterised by a dynamic interplay of climatic, edaphic and biotic factors. Collectively, these ecosystems contribute to over 60% of global terrestrial productivity (Beer et al., 2010). The FSTZ supports a diverse array of species from both forest and savannah biomes, making it a biodiversity-rich zone. High biodiversity improves the resilience and resistance of forest ecosystems, enhancing their ability to withstand changes in climate variables (Isbell et al., 2015).

The transition zone occurs across multiple continents including Australia, Africa, Asia, and South America (Oliveras & Malhi, 2016). In Africa, it is primarily found in West African countries such as Ghana, Cote d'Ivoire, Togo, Benin and Nigeria (Oliveras & Malhi, 2016). In Ghana, this zone spans the middle part of the country, extending across regions such as Bono, Bono East, Ahafo, Ashanti, Eastern, Northern, Savannah, Volta and Oti Region (Ametsitsi et al., 2020). It is one of the country's three primary forest ecological zones, alongside the savannah and high forest zones (Foli et al., 2021). These zones provide important ecosystem services, including carbon sequestration, soil fertility maintenance, and water regulation, which support both ecological functions and human livelihoods.

2.3.1 Ecological and Socioeconomic Importance of the Transition Zone

The FSTZ plays a crucial role in maintaining ecological balance and supporting socioeconomic activities. As a dynamic ecotone, it harbours unique biodiversity by sustaining species from both forest and savannah ecosystems, contributing to ecosystem resilience (Mensah et al., 2020). This ecological gradient fosters diverse plant communities, including dry forests, woodland mosaics, and savannah grasslands, each hosting specialised flora and fauna. In West Africa, the transition zone is home to economically and ecologically important tree species such as *Milicia excelsa* (Welw.) C.C.Berg (Iroko), *Khaya senegalensis* (Desv.) A.Juss. (African mahogany) and *Parkia biglobosa* (Jacq.) R.Br. ex G.Don (African locust bean) (Atsri et al., 2018). These species serve multiple purposes, including timber production, medicine, and non-timber forest products (NTFPs), which directly support local livelihoods (Mascarenhas et al., 2022). These species contribute to local livelihoods by providing timber, medicine and non-timber forest products

(NTFPs). Beyond Africa, other global transition zones, such as the Brazilian Cerrado (Maracahipes-Santos et al., 2018), the Miombo Woodlands of Southern Africa (Rees et al., 2023) and the Australian Tropical Savannas (Banin et al., 2015) provide similar ecological services. These zones foster biodiversity and support key species such as *Chrysocyon brachyurus* Illiger, 1815 (maned wolf) in South America and *Dasyurus hallucatus* Gould, 1842 (northern quoll) in Australia. The presence of these species across different ecological gradients demonstrates the adaptability and significance of transition zones in maintaining biodiversity at both local and global levels.

The FSTZ also serves as a major agricultural hub in Africa. In West Africa, the transition zone supports large-scale production of cash and food crops such as cocoa and cashews, contributing significantly to national economies and global trade (Kadio et al., 2020). Agroforestry is practised within some of the zones, integrating tree species with staple crops, thereby enhancing soil fertility, preventing erosion and promoting sustainable land use (Pabi et al., 2019). The importance of the transition zone for agriculture is not limited to West Africa but extends to other ecologically similar regions worldwide. The Brazilian Cerrado, for instance, is one of the world's largest agricultural frontiers, producing substantial amounts of soybeans, maize and cotton (Klein & Luna, 2021). Likewise, in India's Indo-Gangetic Plains, where the forest-savannah ecotone meets cultivated lands, rice and wheat production dominates, ensuring food security for millions (Sekar & Pal, 2012). Similarly, the Northern Savannas of Australia sustain large-scale cattle grazing and mixed farming systems, further emphasising the critical role of transition zones in global agricultural landscapes (Russell-Smith et al., 2018). These regions, despite their geographical differences, highlight the shared role of FSTZs in supporting human livelihoods through agricultural productivity, while also presenting challenges related to land-use sustainability (Kadio et al., 2020).

In addition to agriculture, the transition zone provides opportunities for ecotourism, which serves as both a conservation and economic tool. Several ecotourism destinations in Ghana are situated within the forest-savannah transition, drawing visitors for their ecological, cultural and historical significance. Notable sites include Kintampo Waterfalls and its adjacent canopy walkway, the Boabeng-Fiema Monkey Sanctuary (BFMS), Fuller Falls and Kristo Buase Monastery (Amankwah et al., 2021; Pabi et al., 2019). These sites generate revenue for local communities, create employment opportunities, and enhance conservation awareness. The Boabeng-Fiema Monkey Sanctuary, for example, is renowned for its sacred status and protection of Colobus and Mona monkeys, reinforcing the intersection between cultural heritage and conservation (Sarfo-Adu et al., 2022). Similarly, the Kogyae Strict Nature Reserve (KSNR), the only protected area in Ghana classified as an IUCN Category Ia strict nature reserve, plays a critical role in preserving biodiversity while also supporting ecotourism and scientific research (Amankwah et al., 2024). Globally, other notable ecotourism-driven FSTZs include the Serengeti-Mara ecosystem in East Africa, known for the annual wildebeest migration (Mahony, 2020); the Pantanal wetlands of Brazil and Bolivia, a biodiversity hotspot (Navarro et al., 2020); and Kakadu National Park in Australia, which blends indigenous cultural heritage with ecological conservation (Russell-Smith et al., 2017). These regions illustrate the vital role of ecotourism in promoting environmental sustainability while contributing to local economies.

Beyond its ecological and economic contributions, the transition zone plays an essential role in hydrological regulation and climate stabilisation. The vegetation cover in FSTZs helps maintain water cycles, recharge groundwater, and regulate microclimates, ensuring the stability of surrounding ecosystems (Boakye et al., 2017). In Ghana, for example, the forested areas within Kogyae Strict Nature Reserve help protect the tributaries of the Afram River, while the Beten and Daworo rivers traverse the Boabeng-Fiema Monkey Sanctuary, underscoring the hydrological significance of these ecosystems. The importance of transition zones in climate regulation extends to other regions as well. The Amazon-Cerrado transition in Brazil plays a critical role in controlling regional rainfall patterns (Maracahipes-Santos et al., 2018), while the African Sahel region benefits from agroforestry interventions that combat desertification and maintains moisture retention in soils (Klein et al., 2015). In India, the Deccan Plateau, which forms a transition between tropical forests and dry grasslands, influences monsoonal rainfall distribution (Riedel et al., 2021). The capacity of transition zones to regulate climate is particularly significant in the context of climate change, as shifts in temperature and precipitation patterns threaten the stability of these ecosystems.

2.3.2 The Role of the Forest-Savannah Transition Zone in Carbon Sequestration and Climate Change Mitigation and Adaptation

Tropical forests are productive and carbon-dense ecosystems (Adu-Poku et al., 2023). In the absence of disturbance, these forests serve as carbon sinks. That is, they store more carbon than they release and can exist for decades. The mixture of forested and open savannah landscapes contributes significantly to carbon storage, particularly through tree biomass and soil organic matter. This helps mitigate the effects of climate change by reducing atmospheric CO_2 levels.

In contrast, forest degradation and deforestation result in the release of greenhouse gases (GHGs), notably carbon dioxide (CO_2), along with nitrous oxide (N_2O) and methane (CH_4), in cases of forest fires. These emissions contribute to climate change and global warming that have adverse impacts on the environment and human populations (Shivanna, 2022). Forest sequesters 30% of CO_2 released through anthropogenic activities (Magnússon et al., 2016). On the other hand, deforestation and forest degradation account for 12-20% of global anthropogenic greenhouse gas emissions (Saatchi et al., 2011).

Reducing Emissions from Deforestation and Degradation, conservation, sustainable management of forests and carbon stock enhancement (REDD+) is an initiative under the United Nations Framework Convention on Climate Change (UNFCCC), building upon the first REDD (Reducing Emissions from Deforestation and Degradation). It built upon the foundational REDD program, expanding its goals to include forest conservation, sustainable forest management and carbon stock enhancement, alongside efforts to curb deforestation and forest degradation (Minang & Murphy, 2010). Furthermore, Sustainable Development Goals (SDGs) 15 and 13 aim to protect, restore and promote the sustainable use of terrestrial ecosystems, manage forests sustainably, combat desertification, reverse land degradation, halt biodiversity loss and take urgent action to combat climate change and its impact.

Ghana joined the REDD+ initiative in 2008, through the World Bank's Forest Carbon Partnership Facility (FCPF) Readiness Programme, and has been an active participant. Initially, Ghana's REDD+ strategy focused on high forest zones but later expanded to include other ecological zones (National REDD+, 2017). Ghana's REDD+ implementation seeks to establish climate-smart production systems that substantially reduce emissions from deforestation and forest degradation over the next two decades while enhancing carbon stocks and conserving biological diversity by preserving the country's forests (National REDD+, 2017). The forest-savannah transition zone in Ghana holds a substantial amount of carbon stock. Enhancing this stock through curbing anthropogenic activities serves as a key to climate change mitigation strategies (Amankwah et al., 2024; Awé et al., 2021).

2.3.3 The Role of Soil Properties in Shaping Vegetation and Ecosystem Functionality in Tropical Forests and Transition Zones

There is increasing evidence that soil nutrients influence ecosystem functionality and tree species in tropical forests. Veenendaal et al. (2014) observed that soil properties such as calcium, magnesium and potassium contents influence tropical vegetation structure and the distribution of woody species distribution. The authors proposed further exploration of this relationship in transition zones across Africa, Australia and South America. Sellan et al. (2019) corroborated that soil nutrients, especially soil acidity, shape forest features by influencing species distribution, richness, composition and structure in Malaysian forests.

Ding et al. (2021) confirmed that soil nutrient availability affects soil microbial activity, consequently influencing ecosystem functionality across forest types in subtropical regions of China. Thammanu et al. (2021) demonstrated that soil moisture and organic matter are among the top five factors explaining the characteristics of different forest stands in northern Thailand. Furthermore, Adu-Bredu et al. (2021) found that soil chemical properties explained 67.5% of the total variation in carbon stocks in the savannah zone of Ghana.

Thakur et al. (2022) reported that tree species composition in tropical Indian forests is influenced by soil properties, such as bulk density and Soil Organic Carbon (SOC), along with climate and anthropogenic activities. Mensah et al. (2023) noted that soil fertility influences aboveground carbon through woody species diversity, richness and structure in semi-arid savannahs. Valencia et al. (2024) confirmed that soil variables, like cation exchange capacity (CEC) and SOC, significantly affect canopy cover in the transition zones of South America. Haas-ek et al. (2024) further confirmed that soil properties have a positive correlation with vegetation structure.

2.3.4 Anthropogenic Pressures and their Impact on the Forest-Savannah Transition Zone

Anthropogenic pressure continues to threaten tropical forests and the transition zones. Ding et al. (2021) identified the conversion of natural forests to plantations as a contributor to the loss of tree diversity in the subtropical forests of China. Furthermore, Maracahipes-Santos et al. (2018) corroborated that anthropogenic fires lead to the degradation of savannahs in the Cerrado-Amazon transition zone.

Goetze et al. (2006) observed that increased deforestation around the Comoe National Park in the transition zone of Cote d'Ivoire has led to forest fragmentation, risking the degradation of the remaining natural forests within the park. Additionally, Dimobe et al. (2018) corroborated that anthropogenic activities have reduced carbon stocks and the biodiversity of savannahs in the semi-arid regions of Burkina Faso.

Anthropogenic activities such as hunting, charcoal burning and illegal logging are prevalent in BFMS and KSNR (Amankwah et al., 2021; Ayivor & Ntiamoa-Baidu, 2015; Janssen et al., 2018; Oduro-Ofori et al., 2015). Most households in these regions are engaged in agriculture and depend on it for their livelihoods, with many farmers practising slash-and-burn agriculture and clearing the forests for farmlands (Amankwah et al., 2021). Hunting and charcoal burning increases the chances of fires in the transition zone, which already has dry vegetation (Awoonor, 2012; Janssen et al., 2018; Lambon et al., 2023)

In the next century, anthropogenic climate change is expected to play a major role in the extinction of many species (Cahill et al., 2013). The primary drivers of deforestation in the transition zone include the clearing of forest land for agriculture and settlements, as well as the exploitation of forests for timber and non-timber products- all of which are anthropogenic activities (Owusu & Essandoh-Yeddu, 2018).

2.4 Vegetation Dynamics of BFMS and KSNR

Understanding vegetation dynamics is essential for assessing ecosystem health, biodiversity conservation, and the sustainability of natural resources. Changes in vegetation structure and composition over time are influenced by both natural and anthropogenic factors, including climate variability, land use practices, and conservation interventions. The Boabeng-Fiema Monkey

Sanctuary (BFMS) and the Kogyae Strict Nature Reserve (KSNR) represent key ecosystems within the forest-savannah transition zone of Ghana, each with distinct vegetation patterns shaped by ecological and human-induced processes.

This section synthesises research conducted on the vegetation of BFMS and KSNR between 2018 and 2024, highlighting trends in species composition, habitat changes, and key drivers of vegetation shifts. Studies on BFMS have focused on the conservation status of woody species and land cover changes, emphasising the impacts of human activities on forest integrity. In contrast, research on KSNR has been more extensive, covering aspects such as species composition, forest cover change, seedling performance, carbon cycling, root dynamics, and the effects of fire and anthropogenic disturbances. These findings contribute to a broader understanding of vegetation dynamics in the forest-savannah transition zone and inform conservation strategies aimed at enhancing ecosystem resilience.

2.4.1 The Vegetation of BFMS from 2018-2024

Three papers were published on the vegetation of BFMS from 2018 to 2024. Djagbletey et al. (2021) researched the composition and the conservation status of woody plants in BFMS, identifying sixty-six woody plant species out of the 842 individuals sampled. The study highlighted the presence of woody species listed as near threatened, vulnerable and endangered, emphasising the sanctuary's significance for in-situ conservation. Amankwah et al. (2021) investigated the changes in vegetation cover from 1992 to 2018, revealing a decrease in closed forests (245 ha) and an increase in open forests (123 ha) and farmlands (40 ha). These changes were attributed to population growth and anthropogenic factors such as farming, hunting and illegal felling, which pose a threat to biodiversity and sustainable ecotourism. Amankwah et al. (2024) assessed the effects of anthropogenic activities on carbon stock in the sanctuary from 1992 to 2023, revealing a total loss of 40,236 Mg C while also highlighting the substantial carbon storage potential of the sanctuary.

Overall, BFMS remains a vital biodiversity hotspot with considerable carbon sequestration potential. Future research and conservation efforts should focus on strengthening protection measures, restoring degraded areas, and promoting community engagement to ensure the long-term sustainability of the sanctuary.

2.4.2 Vegetation of KSNR from 2018-2024

During this period, KSNR received considerable attention in terms of vegetation research, with fourteen published papers addressing various aspects. Armani et al. (2018) assessed the compositional pattern of the overstorey and understorey vegetation, identifying 76 woody species dominated by forest and savannah species. However, the study noted limited stratification due to factors such as fire and drought. Janssen et al. (2018) examined historical changes in the dry forest cover from 1984 to 2015 using remote sensing and secondary data. Their research revealed clearance of the dry forests in the restricted area of the reserve and annual fire occurrence linked to a lack of definite management guidelines and policies and settler encroachment. Julier et al. (2018) analysed pollen from the vegetation types. The studies showed the prevalence of the Poaceae pollen and suggested that the Poaceae family best reflects the transition zone. Moore et al. (2018) investigated carbon cycling and biomass allocation of forests along a rainfall gradient in West Africa. Their findings indicated that climate influences aboveground and belowground carbon more significantly than net primary productivity, with dry forests allocating 40% to 50% of their carbon to wood production. Thomson et al. (2018) utilised Unmanned Aerial Vehicle (UAV) imagery to map the leaf spectra. The authors reported that UAVs broaden the range of measurable qualities and improve the accuracy of trait estimation.

Issifu et al. (2019) assessed seedling performance across different vegetation types, noting the superior performance of savannah species. Ametsitsi et al. (2020) evaluated the relationship between woody plant functional types and soil parameters. Ibrahim et al. (2020) examined root biomass dynamics and necromass patterns, revealing the influence of seasonal water availability on root biomass. Oliveras et al. (2020) studied the influence of taxonomy and environment on leaf traits alongside tropical abiotic gradient, emphasising their role in community assemblage. Shenkin et al. (2020) investigated the effect of ecosystem and phylogeny on tree crowns across regions and found significant variation attributable to the local ecosystem and phylogenetic predictors.

Huaraca Huasco et al. (2021) examined fine root dynamics across rainforest ecosystems. The authors identified soil chemistry and physics as the main drivers. Issifu et al. (2021) evaluated the response of tree seedlings to grass competition and fire revealing resistance of the transition seedlings to fire compared to seedlings in the forest zone.

In 2022, there was no publication on the vegetation of KSNR. However, Lambon et al. (2023) investigated the influence of charcoal burning on vegetation identifying species that are becoming rare and endangered due to charcoal production. Amankwah et al. (2024) assessed the effect of anthropogenic on carbon stock, reporting a total carbon loss of 272,109 Mg C and highlighting the carbon sequestration potential of the nature reserve.

The research on KSNR's vegetation from 2018 to 2024 highlights significant ecological dynamics, emphasising the impact of both natural and anthropogenic factors on forest composition, structure, and function. Studies have documented changes in species composition, the effects of fire, drought, and human activities such as settler encroachment and charcoal production. Findings underscore the vulnerability of dry forests and transition zones, particularly in the absence of clear management strategies. Despite advancements in vegetation monitoring using UAV imagery, remote sensing, and pollen analysis, the lack of publications in 2022 suggests potential research gaps or shifts in focus. The ongoing assessment of carbon stock and sequestration potential (Amankwah et al., 2024) emphasises the reserve's role in climate change mitigation. Future research should prioritise long-term ecological monitoring, sustainable management strategies, and conservation interventions to safeguard KSNR's biodiversity and ecosystem services.

2.5 Clean Development Mechanism (CDM) under the Kyoto Protocol and Carbon Finance

The Clean Development Mechanism (CDM) is a market-based instrument established under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) (Naoki, 2004). It allows developed countries to meet their greenhouse gas (GHG) emission reduction targets by investing in emission reduction projects in developing countries. These projects often focus on renewable energy, energy efficiency, afforestation, reforestation and generate Certified Emission Reductions (CERs), commonly known as carbon credits, which can be traded in international carbon markets (Bortoletto et al., 2023).

CDM projects contribute to sustainable development by fostering technology transfer, creating employment opportunities, and enhancing environmental sustainability. For example, reforestation projects in Uganda under the CDM framework have successfully restored degraded landscapes while generating carbon credits (Hajdu et al., 2016). The revenue from carbon credits provides financial incentives for developing nations to engage in climate-friendly projects, thus contributing to global efforts to mitigate climate change.

Carbon markets play a crucial role in financing climate action by enabling the trading of emission reduction credits. The European Union Emissions Trading System (EU ETS) is one of the largest carbon markets, facilitating the trade of allowances and CERs to achieve cost-effective emission reductions (Dechezleprêtre et al., 2023). However, challenges such as fluctuating carbon prices, additionality concerns and limited participation from least-developed countries have raised questions about the effectiveness of CDM in achieving long-term climate goals.

To strengthen the impact of carbon finance, initiatives such as the Paris Agreement's Sustainable Development Mechanism (SDM) aimed to enhance transparency and environmental integrity in carbon trading (Puno, 2021). By improving governance structures, ensuring equitable benefit distribution and aligning with broader conservation objectives, carbon finance can serve as a vital tool in mitigating climate change while supporting biodiversity conservation and sustainable development initiatives.

2.6 Methodological Advancement in Forest Management: GIS and Remote Sensing

Advances in geographic information systems (GIS) and remote sensing have revolutionised forest ecosystem monitoring by providing cost-effective, efficient and accurate tools for collecting, analyzing and visualizing forest-related data (Pechanec et al., 2018). These technologies play a vital role in forest conservation, aiding in the monitoring of forest cover changes, assessment of forest health, estimation of biomass and carbon stocks, and identification of forest fire risks (Dybala et al., 2019; Food and Agriculture Organization [FAO], 2007). Satellite imagery from sources such as Landsat, MODIS, and Sentinel-2 has enabled the detection of deforestation patterns, forest fragmentation and land-use changes over time (Janssen et al., 2018). Additionally, vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) have been widely used for vegetation health assessment (Ametsitsi et al., 2020). Light Detection and Ranging (LiDAR) technology has enhanced forest biomass estimation and structural complexity analysis, leading to more precise forest conservation assessments (Saatchi et al., 2011; Vastaranta, 2012). By integrating satellite data, LiDAR, and field-based measurements, researchers can generate high-resolution insights into forest structure, canopy dynamics, and biodiversity distribution.

Globally, GIS and remote sensing have been applied to monitor forest changes in various ecosystems. For instance, Mishkin & Navarrete Pacheco (2022) assessed the conservation status of the Monarch Butterfly Biosphere Reserve (MBBR) in Mexico using satellite and remote sensing technologies. Kucuker et al. (2015) mapped forested areas in Turkey through satellite-based land-use classification. Amponsah et al. (2022) conducted a detailed mapping of Atwewa Forest in Ghana using satellite imagery and ground-truth data collection, revealing its current conservation status. Amankwah et al. (2021; 2024) mapped forest changes in protected areas of Ghana, integrating satellite imagery, field measurements, and allometric models to analyze deforestation trends. Nyamugama & Kakembo (2015) mapped and estimated above-ground carbon in South African forests using remote sensing techniques. In Algeria, Zerouali et al. (2023) leveraged GIS and remote sensing to monitor forest cover changes, while Arroyo et al. (2023) used these technologies to assess soil organic matter fluctuations in Mexico. Thomson et al. (2018), demonstrated the effectiveness of UAV technology in monitoring habitat changes in the strict nature reserve in Ghana, facilitating real-time vegetation assessments. These case studies underscore the broad applicability of GIS and remote sensing in forest ecosystem management across different ecological regions.

These methods have significantly improved the accuracy of carbon stock assessments by enabling large-scale measurements of biomass and soil organic carbon. Traditional field-based methods for carbon estimation are often labour-intensive and spatially limited. However, satellite imagery and UAV (unmanned aerial vehicle) technology allow researchers to conduct large-scale vegetation assessments efficiently. For example, Amankwah et al. (2024) utilised remote sensing to assess the influence of anthropogenic activities on carbon stocks in BFMS and KSNR. Baral (2011) mapped the carbon stock of the subtropical forests of Nepal using Geo-Eye and Worldview satellite imagery. Pechanec et al. (2018) modelled multiple carbon pools in the Czech Republic habitats in addition to biomass using remote sensing.

At the national and global scales, remote sensing data has been integrated into carbon monitoring frameworks, such as the REDD+ initiative under the United Nations Framework Convention on Climate Change (UNFCCC). This initiative aims to reduce emissions from deforestation and forest degradation while enhancing carbon stock through sustainable forest management (Minang & Murphy, 2010). In Ghana, the implementation of REDD+ has expanded from high forest zones to include other ecological regions, emphasising the importance of climate-smart production systems and carbon stock enhancement (National REDD+, 2017).

Recent advancements in machine learning have further enhanced the capabilities of GIS and remote sensing for forest monitoring. Machine learning algorithms applied to satellite imagery can automate the detection of land cover changes and predict future deforestation trends (Brovelli et al., 2020). Tariq et al. (2023) highlighted the use of artificial intelligence in classifying vegetation types and detecting deforestation drivers, significantly improving monitoring efficiency. By integrating machine learning models with remote sensing data, researchers can develop predictive frameworks for sustainable forest management and biodiversity conservation.

The integration of GIS, remote sensing, and advanced analytical techniques has transformed forest ecosystem monitoring, improving the accuracy of vegetation assessments and carbon calculations. These technological advancements not only facilitate large-scale forest monitoring but also support global conservation initiatives and climate change mitigation efforts. The continued application of GIS and remote sensing, coupled with emerging machine learning techniques, will be crucial in ensuring sustainable forest management and protecting critical biodiversity hotspots worldwide.

2.7 Assessing the Conservation Status of Forests

The conservation status of forests is an important indicator of ecosystem health, biodiversity integrity and resilience to anthropogenic pressures. Understanding the extent of forest degradation, habitat fragmentation, and species loss is essential for designing effective conservation strategies. This section reviews key literature on methodologies for assessing forest conservation status, including remote sensing techniques, biodiversity indices, ecosystem services evaluation, and policy frameworks. Several methodologies have been developed to assess the conservation status of forests, each providing different insights into forest health and biodiversity trends. These methodologies include genetic, ecological and spatial assessment techniques.

2.7.1 Genetic Heat Index

The Genetic Heat Index (GHI) is a bioquality assessment tool developed by Hawthorne & Abu-Juam (1995) and later updated by Hawthorne & Gyakari (2006) under the International Union for Conservation of Nature (IUCN) forest conservation programme. It evaluates the conservation value of forests based on the rarity and degree of endemism. This index provides a quantitative measure of a forest’s conservation priority by considering the presence of globally rare and ecologically significant species. GHI is determined using a star rating system, which categorises species based on their rarity both within Ghana and on an international scale. The classification considers ecological and taxonomic factors, assigning different weights to species according to their conservation importance.

The GHI for a particular forest or study area is calculated by averaging the weighted star ratings of all species found in that location. A higher GHI score indicates a greater proportion of rare, endangered or endemic species, signifying a higher conservation value and significance. This method allows for the comparison of different forests and helps in prioritising areas for conservation efforts. The GHI methodology has been widely applied to assess the conservation status of tropical forests, demonstrating its effectiveness in different ecological contexts. Studies have successfully utilised GHI in: Ghana (Djagbletey et al., 2021; Owusu-Prempeh et al., 2018), Cameroon (Tchouto et al., 2006) and other tropical forests (Marshall et al., 2016). These studies highlight the adaptability of GHI in identifying forests with high conservation priority and guiding biodiversity conservation strategies. Given its effectiveness, this methodology can be extended to evaluate the conservation status of other tropical forests beyond West Africa.

2.7.2 Red List Index

The Red List Index (RLI), developed by the IUCN, is a key metric for assessing trends in species extinction risk over time (Butchart et al., 2007). It is particularly useful for evaluating the conservation status of forest-dependent species and identifying priority areas for conservation efforts. The RLI value ranges from 0 to 1, where a value closer to 1 indicates that most species in the ecosystem are categorised as least concerned, signifying a lower risk of extinction and a relatively stable ecosystem. Conversely, a value closer to 0 suggests that most species face high extinction risk, indicating severe biodiversity loss and an urgent need for conservation interventions. By monitoring changes in species status over time, the RLI provides insights into biodiversity trends, the effectiveness of conservation measures, and the impact of environmental changes on species survival. It has been widely applied in conservation assessments across different forest ecosystems, including studies in Ghana (Owusu et al., 2022), tropical forests (Marshall et al., 2016), China (Chen et al., 2020) and Peru (Ames-Martínez et al., 2021). These studies demonstrate how RLI can be used to prioritise conservation efforts, identify threatened species, and guide sustainable forest management strategies.

2.7.3 Forest Integrity Assessment

The Forest Integrity Assessment (FIA) is a structured and efficient tool designed to evaluate the condition of forests, offering a rapid, accessible and cost-effective approach to conservation assessment. It serves as a valuable resource for forest conservation planning, biodiversity monitoring, and ecosystem management across different forest landscapes (Chojnackyı, 1996; Suggitt et al., 2021). The FIA provides a practical alternative to resource-intensive conservation assessments that require specialised expertise and extensive field surveys, making it a widely applicable tool for assessing the ecological health and integrity of forests. Developed by the High Conservation Value Resource Network (HCVRN) in collaboration with the Southeast Asia Rainforest Research Partnership (SEARRP), the FIA tool was initially designed for use in Malaysia's tropical forests (Suggitt et al., 2021).

However, its applicability extends to a wide range of forest conservation schemes, including sustainability standards for responsible forest management, community forestry initiatives supporting local conservation efforts, forest restoration projects aimed at improving degraded ecosystems and protected areas management to enhance conservation planning (Suggitt et al., 2021). A key advantage of the FIA tool is its accessibility; it does not require expert knowledge or extensive resources, making it suitable for use by forest managers, conservation organisations and local communities. This inclusivity enables a broader range of stakeholders to participate in forest conservation and implement targeted interventions to enhance ecosystem integrity. Several studies have demonstrated the efficacy and reliability of FIA in assessing forest conservation status. For example, Tierney et al. (2009) used FIA to evaluate the conservation condition of Acadia National Park in the United States, while Suggitt et al. (2021) applied the tool to assess tropical forests. Additionally, Fitts et al. (2022) further validated the effectiveness of FIA in monitoring forest conditions across different ecological settings. These studies confirm that FIA is a robust, scalable, and adaptable method for assessing forest health across diverse geographic regions.

2.7.4 Biodiversity Intactness Index

The Biodiversity Intactness Index (BII) is a key ecological indicator that quantifies the average abundance of native species within a given geographical area relative to their reference populations under minimal human disturbance (Faith et al., 2008). The BII provides a broad, standardised measure of biodiversity change, helping assess the overall health of ecosystems and track the impact of land-use changes, habitat degradation, and conservation efforts (De Palma et al., 2021). It is particularly useful across various taxonomic groups, as it accounts for a wide range of species richness and abundance trends (Scholes & Biggs, 2005).

The BII estimates how native terrestrial species populations compare to their expected abundance levels in the absence of significant human impacts. A high BII value indicates relatively intact ecosystems, while a low BII indicates substantial biodiversity loss due to factors such as deforestation, habitat fragmentation, and land-use changes (De Palma et al., 2021). The BII has been widely applied in conservation research across different ecosystems with notable studies that have affirmed its reliability. Scholes & Biggs (2005) used BII to assess forest conditions in Southern Africa and recommended it as a simple yet practical tool for monitoring biodiversity trends, while also cautioning that it is sensitive to key ecological and anthropogenic factors and De Palma et al. (2021) applied BII to assess tropical and subtropical biomes, demonstrating its relevance in diverse ecological contexts. More recently, Liu et al. (2025) conducted a comprehensive assessment of biodiversity intactness across forest ecosystems in Africa, Asia, and Europe, confirming the reliability of BII as a robust measure for biodiversity monitoring.

CHAPTER 3

MATERIAL AND METHODS

3.1 Study Area

3.1.1 Description of Study Area

The study was conducted in two wildlife-protected areas within Ghana's forest-savannah transition zone: Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR) (Figure 3.1). These areas are important for biodiversity conservation, providing habitats for diverse flora and fauna. BFMS functions both as a biodiversity conservation site and an ecotourism destination. In contrast, KSNR is designated as a strict nature reserve under the International Union for Conservation of Nature (IUCN) Category 1a, dedicated solely to scientific research and ecosystem preservation (Janssen et al., 2018). The Wildlife Division of the Ghana Forestry Commission manages the study area.

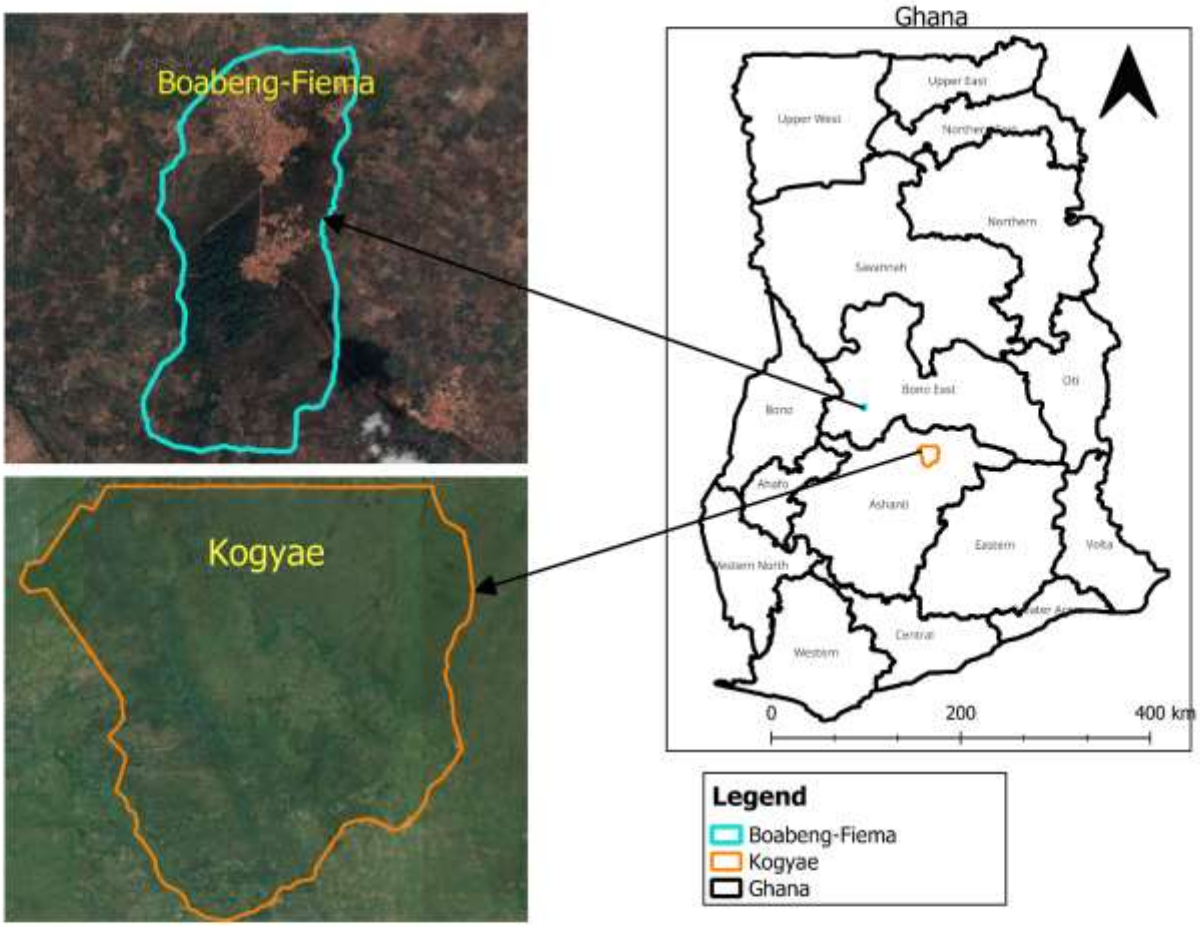

Figure 3.1: Map showing the geographical location and spatial extent of the Boabeng-Fiema Monkey Sanctuary (BFMS, top) and Kogyae Strict Nature Reserve (KSNR, bottom), the two primary study sites located within the forest-savannah transition zone of Ghana.

3.1.2 Geographical Location and Extent

BFMS is located in the Nkoranza North District in the Bono East Region. It covers an area of 535.68 hectares (ha) and falls within longitudes 1°41"10' West to 1°42"15' West and latitudes 7°41"30' North to 7°43"33' North (Amankwah et al., 2021). The sanctuary is surrounded by communities including Akrudwa Panin, Akrudwa Kumaa, Busunya, Kokrompe, Senya, Bomini, Boaman, Odumase, Domeabra and Yefra (Amankwah et al., 2021; Kankam & Sicotte, 2013). KSNR is located in the Sekyere Central District of the Ashanti Region and spans an area of 33,000 ha. The reserve lies within coordinates 7°08' N to 7°21' N and 0°59' W to 1°14' W (Janssen et al., 2018). Communities within the nature reserve are Domeabra, Sankasaase, Njaya and Congo Nkwanta (Afriyie et al., 2021a).

3.1.3 Climate and Metrological Patterns

The study area is characterised by a tropical climate with distinct wet and dry seasons. BFMS experiences a bi-modal rainfall pattern, with major rains occurring from March to June and minor rains from September to November. The average annual precipitation of the sanctuary ranges from 1200 mm to 1400 mm, with an annual temperature of approximately 26°C (Amankwah et al., 2021). BFMS has an average elevation ranging from 321 to 396 meters (m) above sea level. Similarly, KSNR receives an average annual rainfall of 1200 to 1300 mm and bimodal rainfall patterns. However, its average temperature is slightly higher at 28°C (Ayivor et al., 2015) influenced by its relatively lower elevation of approximately 180m above sea level.

3.1.4 Vegetation and Fauna

The vegetation of both sites represents a unique ecological gradient, transitioning between forested landscapes and savannah woodlands. This vegetation structure is shaped by both natural factors such as soil nutrients and hydrology, as well as anthropogenic influences including land use practices. BFMS is predominantly composed of dry semi-deciduous forests interspersed with patches of savannah woodland. The sanctuary is home to a sacred grove that has contributed to wildlife conservation due to traditional conservation. The vegetation of the sanctuary serves as a habitat for three species of primates: *Colobus vellerosus* (I.Geoffroy Saint-Hilaire, 1834), *Cercopithecus campbelli* subsp. *lowei* (Thomas, 1923) and *Galago senegalensis* (É.Geoffroy

Saint-Hilaire, 1796). The *C. vellerosus* monkey is listed as critically endangered on the IUCN Red List (Amankwah et al., 2021; Kankam et al., 2013). KSNR, in contrast, is predominantly composed of woodland savannah with fragmented areas of semi-deciduous forest. Its vegetation supports primate species including the putty-nosed monkey, king colobus and baboon (Afriyie et al., 2021b). The presence of key species such as the putty-nosed monkey (Cercopithecus nictitans Linnaeus, 1766), king colobus (Colobus polykomos Zimmermann, 1780) and baboon (Papio anubis Lesson, 1827) (Afriyie et al., 2021b) highlights the ecological importance of the reserve.

3.1.5 Hydrology and Watershed

The hydrological network of BFMS includes two major rivers: Beten and Daworo Rivers, which traverse the forest of BFMS. These water bodies are essential in maintaining the ecological integrity of the sanctuary, supporting both terrestrial and aquatic biodiversity. KSNR plays a fundamental role in protecting the tributaries of the Afram River (Boakye et al., 2017). The availability of year-round moisture from these tributaries influences species composition and ecosystem productivity within the reserve.

3.1.6 Land Use and Anthropogenic Pressures

BFMS and KSNR are situated within an agriculturally active landscape, where farming is the predominant land use activity. The agricultural sector in Ghana accounts for about 20% of the Gross Domestic Product (GDP) (Nyamekye et al., 2021). The main crops cultivated in the surrounding communities of BFMS include cassava, maize, yam, plantain, groundnut, cowpea, sorghum and tomatoes. Conversely, KSNR is widely known for yam and groundnut cultivation. Additionally, livestock rearing is a common practice in both areas, with other economic activities such as palm wine tapping and cattle rearing being prominent in KSNR. However, various human pressures pose significant threats to the biodiversity of these areas. These include slash-and-burn agriculture, bushfires, charcoal production and hunting practices, all of which contribute to habitat degradation and loss (Amankwah et al., 2021; 2024; Ayivor et al., 2020).

3.1.7 Demographic Trends

The Nkoranza North District, where BFMS is located, has a population of 56,468, while the Sekyere Central District, encompassing KSNR, has a population of 73,228 (Ghana Statistical

Service, 2021). Rural communities surrounding these protected areas rely heavily on agriculture, ecotourism, and small-scale agro-processing for their livelihoods.

3.1.8 Economic Activities

The agricultural produce from BFMS and KSNR is primarily sold in nearby markets to generate household income. In the Nkoranza North District, small-scale agro-processing industries engage in cassava processing, palm oil extraction, soap making, carpentry, blacksmithing, welding, dressmaking, beekeeping, and sawmilling (Ghana Statistical Service, 2021). The service sector includes telecommunications, transportation, education, healthcare, public administration, and financial services. Ecotourism plays a vital role in BFMS, as evidenced by its multiple National Tourism Awards in recognition of its contribution to nature-based tourism. In contrast, KSNR operates under strict conservation policies, permitting only scientific research and conservation-related activities. During fieldwork, beekeeping was observed as a sustainable livelihood activity within the reserve.

3.2 Data Collection

Primary data was collected through field measurements, field observations and questionnaire administration through interviews.

3.2.1 Land Use Land Cover Classification

Landsat satellite images with a spatial resolution of 30 m were obtained for 1992, 2010 and 2023 from the United States Geological Survey (USGS) Centre for Earth Resources Observation and Science (EROS, https://earthexplorer.usgs.gov/), accessed in April 2024. These years were selected to capture long-term changes in forest cover, representing key time intervals relevant to land use land cover. The year 1992 was chosen as a historical baseline to assess past forest conditions before significant human-induced changes. The year 2010 represents an intermediate period to examine trends in forest cover loss or recovery, potentially influenced by conservation efforts and land-use shifts. The year 2023 provides the most recent data to evaluate current forest conditions and assess ongoing deforestation, reforestation, or degradation processes. The selection of these specific years aided in a comprehensive temporal analysis of forest cover dynamics, supporting an understanding of historical and recent trends in land cover change.

3.2.2 Plot Establishment and Inventory

A nested plot design was employed and it facilitated comprehensive data collection. Five main plots were randomly established in each Land Use and Land Cover Classes (LULCCs), resulting in 25 plots each per site and a total of 50 main plots across both sites (BFMS and KSNR). The size of each main plot was $30m\ x\ 30m$ aligns with standard forest inventory methods for assessing vegetation structure in tropical forests, ensuring adequate representation of tree diversity while maintaining feasibility in terms of logistics and sampling effort (Arasa-Gisbert et al., 2024; Djagbletey et al., 2018; Djagbletey et al., 2021; Searle & Chen, 2017). Within each main plot, three subplots of $10m\ x\ 10m$ were laid diagonally, one in the middle of the main plot and the other two towards their respective corners – leading to 75 subplots per site and a total of 150 subplots. This design resulted in 100 plots per site (25 main plots + 75 subplots) and a total of 200 plots across the two sites.

In the main plots, trees with a diameter at breast height (d_{bh}) (stem diameter at $1.3m$ above ground) of more than $10cm$ were measured, while in the subplots, trees with d_{bh} of $2.0cm$ to $10cm$ were measured. Trees with $d_{bh} < 2cm$ were excluded, as they exhibit high mortality rates and are not typically included in structural assessments focusing on mature vegetation and stand dynamics (Searle & Chen, 2017). The d_{bh} was measured with diameter tape, whereas the height of the trees was measured using a laser ace hypsometer (TruPulse). With the assistance of botanists from the Council for Scientific and Industrial Research - Forestry Research Institute of Ghana (CSIR-FORIG), the trees were identified to the species level. For unidentified species, voucher specimens were sent to the laboratory for further identification.

In the subplots, three $1.0m\ x\ 1.0m$ quadrats were laid for the assessment of the non-tree vegetation (herbaceous plants) and forest floor litter (Figure 3.2). Ground litter, including twigs with a diameter of less than $2.0cm$ were collected within the quadrats and fresh weight was determined with a digital weighing scale on the field. The non-tree vegetation (herbs) in the quadrats were removed and fresh weight was determined on the field. Samples of both the litter and herbs were collected and sent to the laboratory at the CSIR-FORIG for the determination of dry-to-fresh weight ratio. The samples were oven-dried at 60℃ for 72 hours to constant weight. Sub-samples were reserved for carbon content analysis.

Figure 3.2: Sampling of litter.

3.2.3 Soil Sampling and Physicochemical Analysis

In each plot, soil samples were collected at five points within each plot from $0cm$ to $15cm$ soil depth using a soil core borer of length $10cm$ and diameter $6cm$ and soil auger (Figure 3.3). This depth was selected because it represents the topsoil layer, which plays a critical role in plant growth and nutrient availability (Dodoo et al., 2023). The majority of fine roots, responsible for water and nutrient uptake, are concentrated within this upper soil layer, making it the most biologically active and relevant for assessing soil properties that influence vegetation structure and composition (Ibrahim et al., 2020; Zhao et al., 2023). Additionally, organic matter content, microbial activity, and soil moisture levels are typically highest in this layer, making it essential for understanding ecosystem processes and plant-soil interactions (Gholoubi et al., 2019; Mokake et al., 2023). Samples taken with the core samplers were used for bulk density determination, whereas those taken with the soil augur were used for the physicochemical analysis.

Fresh weights of the samples earmarked for bulk density determination were taken on the field with a digital weighing balance. The samples were then taken to the laboratory at the CSIR-FORIG. To determine bulk density, the soil samples were sieved to remove roots and stones larger than 2.0mm. The samples were oven-dried at 105℃ for 48 hours to constant weight and the weight was determined with a digital weighing balance. The weight of the dried soil samples and the volume of the core sampler were used to calculate the bulk density.

Figure 3.3: Sampling of soil with a core sampler for physicochemical analysis.

The samples for the physicochemical analyses were taken to the soil laboratory of the CSIR- Soil Research Institute (SRI) in Kumasi. Seventeen soil physiochemical properties were analysed. Soil organic carbon (SOC) was determined by the modified dichromate oxidation method of Walkley-Black (Nelson and Sommers, 1982). Soil pH was determined in a 1:1 soil-water ratio using a glass electrode (H19017 Microprocessor) pH meter. Total nitrogen was determined using the Kjeldahl digestion and distillation procedure (Bremner & Keeney, 1965). Magnesium and Calcium were determined using the EDTA titration method. Sodium and potassium were determined using a flame photometer (Motsara & Roy, 2008; Nelson & Sommers, 1982).

3.2.4 Socio-economic data

The Nkoranza North District, where BFMS is located, has a population of 56,468, while the Sekyere Central District, encompassing KSNR, has a population of 73,228 (Ghana Statistical Service, 2021). However, the target population for this study was not the entire district population, but rather the adult residents of the selected communities. Based on a reconnaissance survey and consultations with local leaders, including community elders and assembly members, the total adult population was estimated at approximately 1,600 individuals. Slovin's formula was employed to determine the appropriate sample size for the socio-economic data collection. The minimum sample size, *n*, required for accuracy in estimating proportions was computed by allowing a 5% margin of error (Equations 3.1) as;

$$n = \frac{N}{(1 + N \times e^2)}. \tag{3.1}$$

where *N* is the population size and *e* is the desired margin of error (expressed as a proportion).

The minimum sample size was computed to be 320 respondents, using Equation 3.1. However, after data collection 300 responses were analysed due to incomplete responses. Some questionnaires were partially filled missing important details required for analysis. The distribution of respondents varied across sites due to differences in population sizes, accessibility, and willingness to participate in the survey. Specifically, in the BFMS area, Boabeng and Fiema had 78 and 72 respondents, respectively, while in the KSNR area, Congo Nkwata, Domeabra, Njaya, and Sankasaase had 40, 49, 41, and 20 respondents, respectively. The selected communities were chosen based on their proximity to the reserves. The variation in sample distribution across communities was influenced by differences in population size, household availability and willingness of respondents to participate in the survey. Communities with larger populations had higher representation, while those with smaller populations contributed fewer respondents.

A semi-structured questionnaire tailored to the local context, comprising both open and closed-ended questions, was developed to gather data on socio-demographic characteristics and conservation practices related to forest conservation from the respondents (Figure 3.4). Prior to the main survey, a pilot study was conducted with a small group to assess the questionnaires' applicability and address any potential misunderstandings. Research assistants from the Forestry

Research Institute of Ghana (FORIG) were trained to assist in data collection. Questionnaires were administered through interviews conducted in the local dialect, Twi, with questions translated from English to accommodate the educational and linguistic backgrounds of the respondents.

The Wildlife Division of the Ghana Forestry Commission and the local authorities, including chiefs and assembly committee, approved the study. The research team followed community entry procedures, including a formal introduction at the chiefs' palaces and consultation with assembly committee leaders. Announcements about the research activities were disseminated through local information centres within the communities. This collaborative approach ensured transparency, respect for local authority and community engagement.

The respondents were fully briefed on the purpose of the research and the scope and confidentiality measures before the interviews. They were informed that participation was voluntary and that they could withdraw at any point. To ensure a representative sample of the population, surveys were conducted at households, workplaces and community centres. Data collection schedules were adjusted to accommodate the farming activities of the community, with interviews conducted in the late afternoons and weekends.

A systematic random sampling method was employed, with the local communities divided into clusters based on specific locations: Boabeng and Fiema in BFMS and Domeabra, Sankasase, Nyaja and Congo Nkwanta in KSNR. Starting points within each community were randomly selected, and households were surveyed along predetermined routes using a fixed sampling interval of every third household (i.e., after sampling one household, the next household was skipped and the subsequent one was surveyed). The transects were spaced approximately 50 metres apart to ensure adequate coverage of the community. For the purposes of this study, a respondent is defined as an individual aged 18 years or older who resides in the selected communities and voluntarily agreed to participate in the survey. Respondents were selected randomly from the eligible population within each of the selected communities. It is important to note that no specific pre-defined protocols or selection criteria were applied to target respondents based on their knowledge or experience related to local forests or conservation practices. This objective explored community perspectives on forest conservation by identifying practices that local inhabitants believed could help preserve the forests of these wildlife-protected areas within the forest-savannah transition zone of Ghana.

Figure 3.4: Administration of questionnaires through interviews.

3.3 Data Analyses

Data for the various activities were analysed to assess ecological patterns, carbon stocks, conservation status and community perspectives. Both quantitative and qualitative datasets were subjected to appropriate statistical and thematic analyses to ensure accuracy.

3.3.1 Carbon Stocks Estimation

3.3.1.1 Biomass Carbon Stock Pools

The aboveground mass of the individual trees was estimated based on height, diameter at breast height (d_{bh}), and wood density using the appropriate allometric model. The Allometric model of Chave et al. (2014) was used for the estimation of the aboveground mass of the individual trees, *AG* (kg), as (Equation 3.2);

$$AG = 0.0673\ x\ (\rho D^2 H)^{0 \cdot 976}. \tag{3.2}$$

where *D*= diameter at breast height (cm), *H*=tree Height (m) and ρ=Wood density (g cm^{-3}). The belowground mass (*BG*) was calculated by multiplying the *AG* by 0.25, a conversion factor (IPCC, 1996; Handavu et al., 2021). The name of the tree species was used as a surrogate for wood density. This means that instead of directly measuring the wood density of each sampled tree, the species-specific average wood density values were obtained from existing databases and literature (Djagbletey et al., 2020; Zanne et al., 2009).

The sum of individual tree mass was used to calculate the biomass, and subsequently, carbon stock at the plot level. The aboveground (*AGC*) or belowground (*BGC*) biomass carbon stock of the trees (Mg C ha^{-1}) was estimated using Equation 3.3 (Adu-Bredu et al., 2021) as;

$$AGC\ or\ BGC = \sum_{i=1}^{n} (AG \text{ or } BG) \times \frac{10000}{A} \times \frac{CFr}{1000}. \tag{3.3}$$

where *A* is the area of the plot (m^2), *n* is the number of trees in the plot and *CFr* is the carbon fraction for the conversion of the tree biomass to biomass carbon stock. The *CFr* value used was 0.4748 (Adu-Bredu et al., 2010).

Carbon stock for litter (L_b) and herbs (H_b) (Mg C ha^{-1}) was estimated using Equation 3.4 (Adu-Bredu et al., 2021) as;

$$H_b\ or\ L_b = \frac{1}{n} \sum_{i=1}^{n} \frac{SD_m}{SF_m} \times TF_m \times \frac{10000}{A} \times \frac{CFr}{1000}. \tag{3.4}$$

where *n* is the number of quadrats, SD_m is the sample dry mass (g), SF_m is the sample fresh mass (g), TF_m is the total fresh mass (kg) and *A* is the area of the quadrat (m^2). Adu-Bredu et al. (2021)

found the carbon fraction of the litter and herbs to be 0.36, and this was used in the conversion of the herbs and litter to biomass carbon stock.

3.3.1.2 Soil Carbon Pool

Soil Carbon Stock (*SCS*) (Mg C ha^{-1}) was calculated using Equation (3.5) (*cf*. Adu-Bredu et al., 2021):

$$SCS = BD \times D_P \times SOC \tag{3.5}$$

where *BD* = bulk density, *SOC* = Soil organic carbon and D_p= soil depth.

3.3.2 Carbon Density

Carbon density, expressed as the Total Carbon Stock (*TCS*), was calculated by summing the carbon stocks of the different carbon pools. This calculation was performed using Equation 3.6 (Pearson et al., 2013; Siraj, 2019).

$$TCS = ACG + BGC + SCS + H_b + L_b \tag{3.6}$$

3.3.3 Carbon Stock from 1992 – 2023

The Land use land cover classification was performed using both unsupervised and supervised classification methods. Accuracy assessment was performed using 200 referenced Global Positioning System (GPS) points obtained from a field survey in the study area. A post-classification method was used for change detection. Woody species were identified and catalogued in the different land use land cover classes (LULCC) within the study area. The LULCCs are closed forest (CF, continuous canopy covering at least 60% obstructing sunlight from reaching the forest floor), open forest (OF, discontinuous canopy cover ranging between 15 and 59%), woodland (WL, scattered trees or shrubs with grass layer), savannah (SV, dominated by a continuous layer of grass with few to no trees) and cropland (CL, area under cultivation). This classification approach provided a comprehensive understanding of the forest cover dynamics in the study area over a three-decade period, aiding in assessing changes due to anthropogenic activities. The *AGC* estimate for each vegetation type was multiplied by its areal extent calculated from the satellite images to estimate the carbon stock for each vegetation type. The results were summed up to obtain the carbon stock for the years 1990, 2010 and 2023.

3.3.4 Carbon Sequestration Potential

Carbon Dioxide Equivalent (CO_{2e}) serves as a metric to convert the various Greenhouse Gas (GHG) estimates into their equivalent amounts in carbon dioxide (CO_2). The molecular weight ratio between carbon dioxide (44) and carbon (12) is 3.67. To determine the carbon sequestration potential of the study area, the *TCS* was multiplied by this CO_{2e} (3.67) conversion factor (Ibrahim et al., 2022; Kauffman & Donato, 2012).

3.3.5 Woody Species Composition and Diversity

Woody species diversity was represented by the Shannon-Wiener Species Diversity Index (*H*, Equation 3.7) (Brouwer et al., 2022; Shannon, 1948). This index takes into account both the number of species present (species richness) and the relative abundance of the species present (species evenness).

$$H = -\sum_{i=1}^{s} \mathcal{P}i \times In(\mathcal{P}i) \tag{3.7}$$

Where *s* is the number of species in the community, *pi* is the relative proportion of species *i* and *In* is the natural logarithm. *H* has a value between 1 and 4, and hardly ever goes above 4.0 (Ortiz-Burgos, 2016). A higher *H* value indicates an increased species diversity within a given community, while lower values correspond to decreased diversity. In cases where $H = 0$, the community consists of a single species (Kiernan, 2014).

Kruskal-Wallis One Way Anova Non-Parametric Test was used to assess the significance of the Shannon-Wiener Diversity Index across the different LULCCs. Prior to the significant tests, normality and homogeneity were evaluated using the Shapiro-Wilk and Levene tests, respectively. R software was used for the analysis.

The Importance Value Index (*IVI*, Equations 3.8, 3.9, 3.10 and 3.11) was employed to measure the ecological importance of woody species identified and key species that contribute significantly to the overall structure and composition of the forest ecosystem (Curtis & McIntosh, 1951; Zhang et al., 2018).

$$IVI = Relative\ Density\ + Relative\ Frequency\ + Relative\ Dominance \tag{3.8}$$

where:

$$Relative\ Density = \frac{Density\ of\ species}{Total\ density\ of\ all\ species}\ x\ 100 \quad (3.9)$$

$$Relative\ Frequency = \frac{Frequency\ of\ species}{Total\ frequency\ of\ all\ species}\ x\ 100 \quad (3.10)$$

$$Relative\ Dominance = \frac{Dominance\ of\ species}{Total\ dominance\ of\ all\ species}\ x\ 100 \quad (3.11)$$

The Sørensen Similarity Coefficient (SSC, Equation 3.12) is a standard and widely used measure of beta diversity, assessing the degree of similarity in species composition between two ecosystems (Chao et al., 2005; Sullivan et al., 2017; Travlos et al., 2018). Beta diversity quantifies species turnover, providing insight to understand how biodiversity changes across spatial scales. In this study, the SSC was employed to evaluate the beta diversity between the two protected sites. The SSC was chosen because it effectively quantifies species overlap between sites based on presence/absence data, making it suitable for assessing differences in species composition between sites. The Sørensen Similarity Coefficient is calculated as:

$$Ss = \frac{2a}{2a+b+c}\ x\ 100 \quad (3.12)$$

where:

Ss = Sørensen similarity

a = number of species common to both sites

b = number of species unique to Site 1

c = number of species unique to Site 2

3.3.6 Explanatory Matrix

Soil physicochemical properties were used as the explanatory variables, while woody species abundance served as the response variable. Seventeen soil physiochemical properties were measured and a variance inflation factor (VIF<5) was employed to exclude highly correlated variables. As a result, eight soil physicochemical properties were retained: base saturation (BS), bulk density (BD), total nitrogen (TN), the potential of hydrogen (pH), phosphorus (P), magnesium (Mg), potassium (K) and sodium (Na). Canonical Correlation Analysis (CCA) was performed to assess the relationship between woody species and the selected soil physicochemical properties.

This multivariate ordination technique was chosen due to its ability to effectively capture and illustrate the extent to which variations in woody species composition can be attributed to these soil properties, thereby identifying the most influential soil factors in species distribution across the study area. A significant test was subsequently conducted to evaluate the statistical significance of the relationships found in the CCA. All analyses were performed using R software (version 4.3.2).

3.3.7 Conservation Status of the Protected Areas

The study employed the Genetic Heat Index (*GHI*) and Red List Index (*RLI*) to evaluate the conservation status of protected areas, providing bioquality data that includes endemism and threat status of the sites. These metrics provide a quantitative assessment of species rarity, extinction risk and overall ecological health.

The GHI (Equation 3.13), developed under the IUCN forest conservation programme by Hawthorne & Abu-Juam (1995) and Hawthorne & Gyakari (2006) measures the degree of endemism within a given area (Djagbletey et al., 2021). It assigns numerical values based on species rarity, facilitating the identification of unique ecosystems and conservation priorities. A higher GHI value indicates the presence of many species with restricted geographic ranges (high endemism), whereas a lower GHI suggests that species are more widely distributed (lower endemism). The GHI is calculated by assigning each species a star rating, which represents a category of global rarity, with corresponding weight (Table 3.1) (Djagbletey et al., 2021; Hawthorne & Abu-Juam, 1995; Hawthorne & Gyakari, 2006; Owusu-Prempeh et al., 2018). According to the categorisation of GHI by Owusu-Prempeh et al. (2018) sites with GHI ≥ 200 are considered to have very high conservation value, while those with 150 ≤ GHI < 200 are categorised as having high conservation value. A considerable conservation value is assigned to sites with 100 ≤ GHI < 150, whereas sites with 50 ≤ GHI < 100 are classified as having low conservation value. Sites with GHI < 50 are regarded as having very low conservation value.

$$GHI = \frac{(GD\ x\ GDwt)+(GN\ x\ GNwt)+(PK\ x\ PKwt)+(RD\ x\ RDwt)+(ST\ x\ STwt)\ x\ 100}{GD+GN+PK+RD+ST} \qquad (3.13)$$

where:

GD = number of Gold Star species; *GN* = number of Green Star species; *PK* = number of Pink Star species; *RD* = number of Red Star species*; ST* = number of Scarlet Star species. *GDwt, GNwt, PKwt, RDwt* and *STwt* are the weight of Gold, Green, Pink, Red and Scarlet Star species, respectively.

Table 3.1: Weight and comments on the star rating of species (Adapted from Hawthorne & Abu-Juam (1995) and Hawthorne & Gyakari (2006)

Star	**Weight for GHI**	**Comment**
Gold	9	These species have a relatively low occurrence both internationally and /or locally. Ghana has a major responsibility for maintaining these species.
Green	0	These species have no particular conservation concern.
Pink	1	These species are widespread and moderately exploited. They are also non-abundant species of high potential value.
Red	1	These species are widespread but under pressure from exploitation. They need careful management and targeted protection measures at both individual tree and whole area levels.
Scarlet	1	These species are widespread but face substantial pressure from heavy exploitation. Exploitation needs to be curtailed if usage is to be sustainable. Protection measures on all scales are vital.

To complement the GHI, the Red List Index (*RLI*), developed by the IUCN (Equation 3.14) was used to assess the international conservation status of the study area showing the extinction risk of species in the areas (Butchart et al., 2007).

$$RDI_t = 1 - \frac{\Sigma_s W_{c\,(t,s)}}{(W_{EX} \times N)} \tag{3.14}$$

where *Wc(t,s)* is the weight for category '*c*' at the time (*t*) for species (*s*), and *N* is the total number of assessed species, excluding those assessed as Data Deficient in the current period and those considered to be 'Extinct' in the year the set of species was first assessed. The weight assigned to Extinct (W_{EX}), Critically Endangered (*CE*), Endangered (*E*), Vulnerable (*V*), Near Threatened (*NT*) and Least Concern (*LC*) is 5, 4, 3, 2, 1 and 0, respectively.

Both GHI and RLI were selected for this study due to their effectiveness in evaluating species rarity, extinction risk, endemism and conservation priority. The GHI quantifies the bioquality of forests by identifying globally rare and ecologically significant woody species, aiding in conservation planning (Hawthorne & Abu-Juam, 1995; Hawthorne & Gyakari, 2006). Its star rating system facilitates site comparisons, ensuring that areas with high conservation value receive appropriate protection. Similarly, RLI provides a standardised method for monitoring extinction risk over time, offering insights, offering insights into ecosystem stability and the effectiveness of conservation measures (Butchart et al., 2007). By integrating both indices, this study delivers a robust assessment of species rarity and vulnerability to extinction, contributing to evidence-based conservation strategies for BFMS, KSNR and other forest ecosystems.

3.3.8 Forest Conservation Practices by Inhabitants of BFMS and KSNR

The data collected from the questionnaires were cleaned, coded and analysed using Statistical Package for Social Sciences (SPSS). The software facilitated data management and computation of descriptive statistics to summarise the socio-demographic variables such as sex, age, educational level, occupation and residential status of respondents.

Exploratory Data Analysis (EDA) was conducted using R software to generate visual representations of socio-demographic variables. Bar graphs were generated to illustrate the distribution of key variables such as sex, age, educational level, occupation and residential status. These visualisations provided a clear overview of respondents' variables.

Respondents' perspectives on forest conservation practices were captured through an open-ended question: "What practices do you think can help preserve the forest in your area?" The responses were grouped into thematic categories — such as wildfire prevention, staffing of forest protection units, community engagement, reforestation, alternative livelihoods and enforcement of forest laws — based on a qualitative coding framework developed during the data review. Each conservation theme was then converted into a categorical variable with multiple outcomes (e.g., 1 = wildfire prevention, 2 = staffing of forest protection units, 3 = community engagement, etc), which were used as the dependent variables for analysis.

Since respondents could mention multiple conservation practices, each theme was treated as a separate outcome. Multinomial logistic regression (MLR) was conducted for each conservation practice to assess whether socio-demographic variables influenced the likelihood of a respondent mentioning each specific conservation practice.

The general form of the MLR model used is:

$$log\left(\frac{P(Y_i = k)}{P(Y_i = 0)}\right) = \beta_0^k + \beta_1^k Age_i + \beta_2^k Sex_i + \beta_3^k Education_i + \beta_4^k\ Residential\ Status_i + \varepsilon_k$$

Where:

Y_i is the categorical variable indicating the specific conservation practice mentioned by respondent i.

P($Y_i = k$) is the probability that respondent i mentioned conservation practice k.

P($Y_i = 0$) is the reference category, representing respondents who did not mention any practice.

β_0^k is the intercept for category k.

β_1^k ,…, β_4^k are the coefficients for the socio-demographic predictors (age, sex, education and residential status) for conservation practice k.

ε_k is the error term for each.

Separate models were estimated for each conservation theme (e.g., wildfire prevention, staffing, education). Statistical significance was assessed at a 95% confidence level ($p < 0.05$) and results were interpreted accordingly to identify demographic predictors of conservation practices.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Woody Species Diversity and Forest Structure in BFMS and KSNR

Understanding the diversity (richness and composition) and structure of woody species in protected areas is fundamental to assessing their ecological integrity and conservation value. Attributes such as species composition, richness, dominance and structural traits provide insights into the ecological health, resilience and functioning of forest ecosystems. This section examines the species richness, abundance, diversity, floristic composition, dominant species and beta diversity of the Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR), highlighting key taxonomic groups and their relative abundance. The Importance Value Index (IVI) was used to evaluate the species' significance and to inform conservation prioritisation.

4.1.1 Species Richness, Abundance, Floristics Composition, Diversity and Structural Attributes across LULCCs

A total of 1,094 individual trees were sampled in the study area, comprising 681 individuals recorded in Boabeng-Fiema Monkey Sanctuary (BFMS) and 413 in Kogyae Strict Nature Reserve (KSNR). In BFMS, 87 woody species were recorded across various land use land cover classes (LULCCs), representing the highest documented species count to date for the sanctuary. Previous studies reported lower numbers: Djagbletey et al. (2021) identified 66 woody species, Wiafe (2014) recorded 49 woody species and Kankam et al. (2013) documented 68 and 70 species in BFMS in 2007 and 2000, respectively. In contrast, 38 woody species were identified in KSNR, aligning with earlier studies. Torello-Raventos et al. (2013) recorded 30 species in KSNR, while Janssen et al. (2018) identified 21 species. Armani et al. (2018), however, documented a higher number of species (76), which was attributed to the inclusion of juvenile individuals. Collectively, these findings highlight the richness of woody species in these protected areas, underscoring their role in biodiversity conservation.

Species richness and abundance followed similar patterns across LULCCs in both sites. The closed forests recorded the highest species richness and abundance, followed by the open forests, woodlands, croplands and savannahs (Table 4.1 and Table 4.2). This pattern is consistent with findings from Isbell et al. (2015), Subashree et al. (2021) and Sullivan et al. (2017), which suggest that intact forests with minimal disturbances provide favourable microhabitat and increased resource availability for diverse woody species. A strong positive correlation (r = 0.9) was found between species abundance and richness, highlighting the ecological importance of tree density in supporting biodiversity through niche diversification and resource partitioning. Species richness enhances the ecological resilience of forest ecosystems, enabling them to better withstand and recover from disturbances while maintaining functional integrity over time (Owusu-Prempeh et al., 2018).

Diversity analysis showed that closed forests had the highest diversity index in BFMS, whereas open forests ranked highest in KSNR. Field observations in KSNR revealed more frequent gaps in the open forests, which may explain the higher diversity, as such gaps enhance light availability and facilitate the regeneration of light-demanding species. Gaps and fire play key roles in forest succession; however, uncontrolled gap formation resulting from anthropogenic activities such as illegal logging and agricultural encroachment can lead to the loss of native species and ecosystem degradation (Hagemann et al., 2022). Statistical analysis revealed a significant difference ($p < 0.05$) in the Shannon-Wiener diversity index across the LULCCs. Species richness also varied significantly across the LULCCs, except in open forests. These findings suggest that LULCCs influence woody species diversity and richness within the transition zones.

Table 4.1: Summary of floristic and structural attributes across LULCCs in BFMS

			Floristic Composition		
	Closed Forest	Cropland	Open Forest	Savannah	Woodland
Families	21	12	18	8	11
Genera	41	16	33	10	15
Species	51	16	37	10	18
Abundance	334	31	212	14	90
Richness	51	16	37	10	18
Shannon	2.3 ± 0.49	1.22 ± 0.37	1.82 ± 0.75	0.67 ± 0.47	1.43 ± 0.81
Evenness	0.84 ± 0.06	0.95 ± 0.03	0.76 ± 0.17	0.97 ± 0.04	0.86 ± 0.08
			Structural Attributes		
Basal Area (cm)	0.05 ± 0.16	0.06 ± 0.09	0.03 ± 0.07	0.02 ± 0.04	0.05 ± 0.12
DBH (cm)	13.56 ± 20.64	23.22 ± 16.78	14.51 ± 13.99	10.39 ± 10.99	14.29 ± 21.84
Height (m)	8.52 ± 10.08	9.12 ± 4.91	9.05 ± 7.98	5.19 ± 4.29	8.61 ± 11.03
Wood density	0.57 ± 0.11	0.59 ± 0.18	0.60 ± 0.15	0.65 ± 1.18	0.31 ± 0.34

Table 4.2: Summary of floristic and structural attributes across LULCCs in KSNR.

	Closed Forest	Cropland	Open Forest	Savannah	Woodland
Floristic Composition					
Families	15	5	13	3	8
Genera	21	9	19	4	10
Species	23	9	20	4	10
Abundance	232	19	115	8	39
Richness	23	9	20	4	10
Shannon	1.53 ± 0.37	0.75 ± 0.78	1.65 ± 0.29	0.10 ± 0.22	1.11 ± 0.28
Evenness	0.71 ± 0.10	0.57 ± 0.52	0.83 ± 0.06	0.36 ± 0.51	0.91 ± 0.07
Structural Attributes					
Basal Area (cm)	0.04 ± 0.07	0.05 ± 0.11	0.04 ± 0.06	0.10 ± 0.07	0.07 ± 0.10
DBH (cm)	17.81± 12.66	15.33 ± 21.34	17.17 ± 13.86	32.86 ± 12.69	21.57 ± 21.08
Height (m)	11.44 ± 9.61	6.76 ± 8.19	8.58 ± 5.59	22.11 ± 9.78	10.47 ± 9.08
Wood density	0.67 ± 0.44	0.33 ± 0.33	0.67 ± 0.14	0.80 ± 0.17	0.42 ± 0.29

4.1.2 Dominant Woody Species and Families in BFMS and KSNR

The composition of dominant woody plant families in BFMS and KSNR highlights differences in vegetation structure and ecological dynamics between the two sites. In BFMS, the dominant families are Fabaceae (19 species), Rubiaceae (8 species) and Euphorbiaceae (8 species). The dominance of these families in the transition zone of Ghana has been corroborated by Djagbletey et al. (2021) corroborated. These families are commonly associated with tropical forests and woodland ecosystems, suggesting a relatively higher prevalence of forest-adapted species in BFMS (Djagbletey et al., 2021; Tchaleu et al., 2024). Similarly, Fabaceae is the dominant family in KSNR, represented by nine species. Fabaceae species are known for their ability to fix nitrogen, which may contribute to their dominance in KSNR, a reserve that experiences seasonal fires and disturbances. In addition to Fabaceae, other prevalent families in KSNR included Anacardiaceae, Meliaceae, Rubiaceae and Sapotaceae, each represented by three species. The presence of these families indicates a mixture of both forest and savannah-adapted species (Bienu et al., 2023; Egbe et al., 2021). Overall, these results indicate that BFMS supports a relatively diverse composition of forest species, while KSNR exhibits a mix of savannah and dry forest species, possibly due to periodic disturbances. Understanding these differences is essential for conservation planning, sustainable management, and restoration efforts aimed at preserving biodiversity and ecosystem function in both reserves.

The majority of the woody species identified in the study area are native species of high economic and ecological value. Figure 4.1 and Figure 4.2 show the distribution of the 12 top tree species in terms of abundance in BFMS and KSNR. Consistently, the closed and open forests emerge as hotspots of woody species abundance, as evidenced by the prevalence of the top identified species within these habitats. Many of the most prevalent woody species identified in the study area, including *Anogeissus leiocarpus* (DC.) Guill. & Perr., *Daniellia oliveri* (Rolfe) Hutch. & Dalziel, *Holarrhena floribunda* (G.Don) T.Durand & Schinz, *Pterocarpus erinaceus* Poir., *Margaritaria discoidea* (Baill.) G.L.Webster and *Terminalia schimperiana* Hochst. ex Engl. & Diels possess significant medicinal properties and have been traditionally used in African ethnomedicine for centuries (Fabiyi, 2021; Hoekou et al., 2017; Obiri et al., 2014). For instance, *Anogeissus leiocarpus* (DC.) Guill. & Perr. has been widely studied for its antimicrobial and anti-inflammatory properties, with its extracts being effective against bacterial and fungal infections. *Daniellia oliveri* (Rolfe) Hutch. & Dalziel, a common species in the forest-savannah transition zone, has been reported to have analgesic and anti-arthritic properties, making it an essential component in traditional remedies for joint pain and inflammatory conditions (Sofidiya et al., 2023). Similarly, *Holarrhena floribunda* (G.Don) T.Durand & Schinz is recognized for its potent antimalarial and anti-diarrheal properties, with alkaloids extracted from its bark and roots showing promising results in the treatment of gastrointestinal disorders and parasitic infections (Hoekou et al., 2017). Additionally, *Pterocarpus erinaceus* Poir., a drought-resistant species, is known for its antioxidant and hepatoprotective properties, with its bioactive compounds playing a role in detoxification and liver health (Noufou et al., 2017). *Margaritaria discoidea* (Baill.) G.L.Webster, another medicinally important species, has been used in traditional medicine for its anti-allergic and wound-healing properties (Obiri et al., 2014). Furthermore, *Terminalia schimperiana* Hochst. ex Engl. & Diels has been documented to exhibit antibacterial and anti-inflammatory effects, making it a vital species for treating skin infections, respiratory diseases, and inflammatory disorders (Fabiyi, 2021). The presence of these species in the study area underscores the ecological and pharmacological importance of preserving forest ecosystems, as they provide medicinal resources that serve as primary healthcare for the local communities.

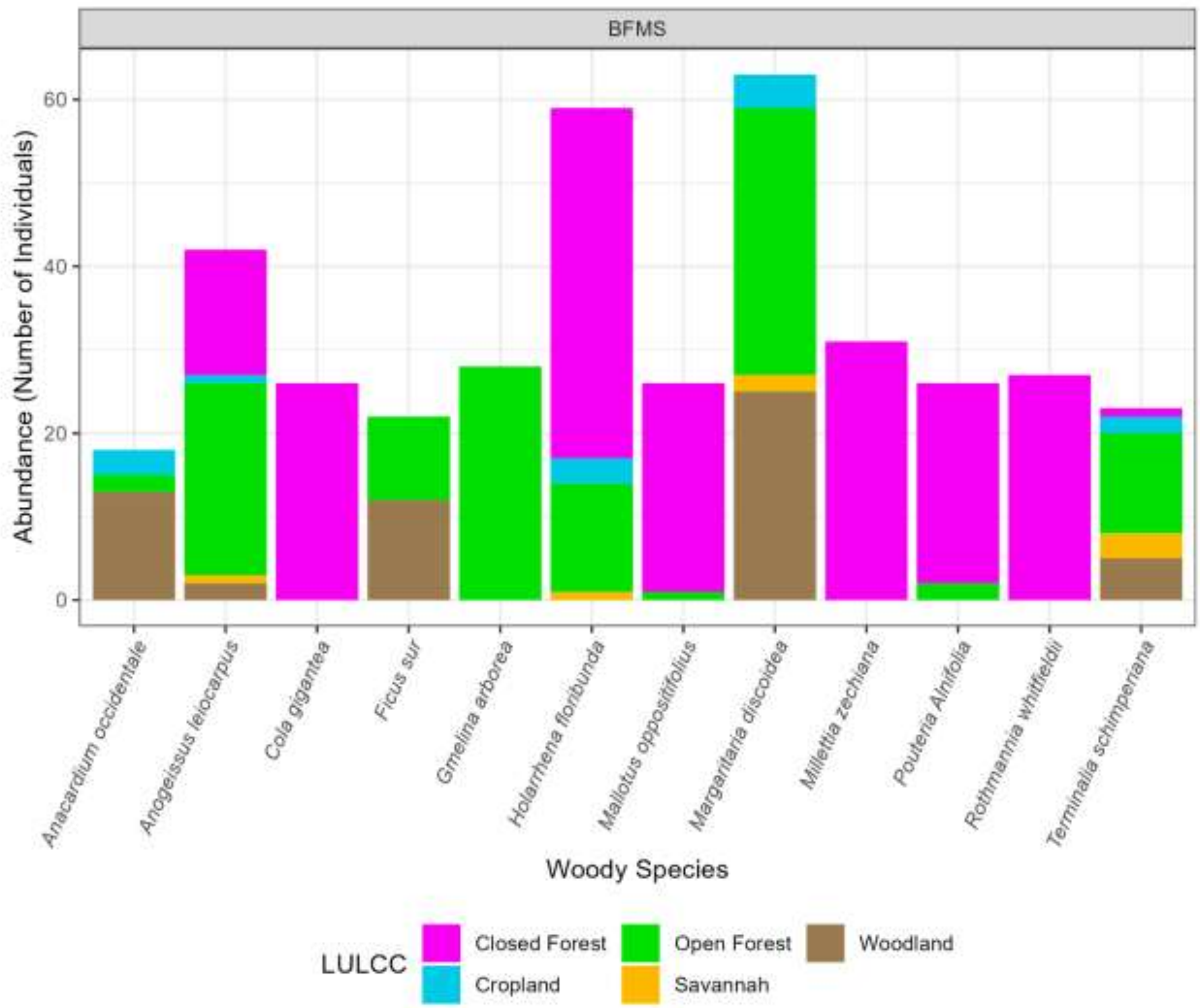

Figure 4.1: Top 12 species across the different LULCCs in BFMS.

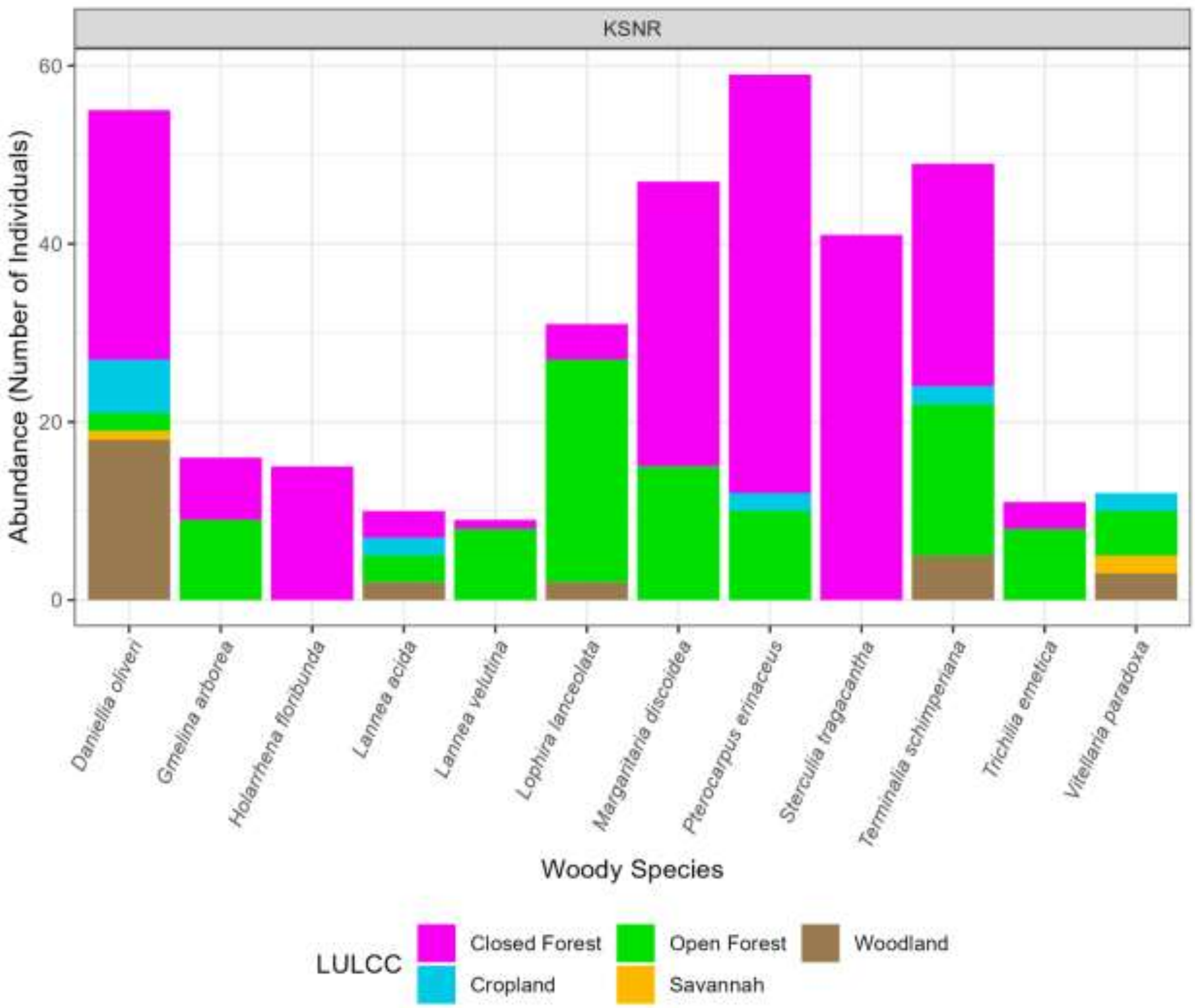

Figure 4.2: Top 12 species across the different LULCCs in KSNR.

The presence of *Anacardium occidentale* L. (cashew), *Gmelina arborea* Roxb. ex Sm. (gmelina) and *Tectona grandis* L.f. (teak) within the protected areas indicates potential disturbances and shifts in land use and land cover, likely driven by anthropogenic activities. These species are exotic and primarily introduced for commercial forestry, agroforestry and land rehabilitation purposes due to their fast growth rates and economic value (Akyereko et al., 2022). Teak and Gmelina are widely cultivated for timber production, while cashew is commonly grown for their nuts and economic benefits to local farmers (Sasidharan, 2021; Tamang et al., 2021). Their presence in the study area suggests prior land conversion activities, such as plantation establishment, logging, or agricultural expansion, which may have led to the displacement of native vegetation and altered ecosystem dynamics. Exotic species often outcompete native species for resources, potentially reducing biodiversity and modifying soil properties, hydrological processes, and habitat structures (Cochard, 2011). Additionally, their proliferation may indicate secondary succession following disturbances such as fire, logging, or shifting cultivation, where degraded landscapes are gradually colonized by non-native species (Maua et al., 2020). The introduction of these species, while economically beneficial, raises concerns regarding their ecological impact, particularly in terms of biodiversity loss, competition with indigenous species, and long-term forest resilience. Understanding the extent of their influence on native woody species composition is important for informing sustainable forest management and conservation strategies in the region.

4.1.3 Beta Diversity of BFMS and KSNR

BFMS and KSNR had 16 woody species in common: *Afzelia Africana* Sm. ex Pers., *Anacardium occidentale* L., *Anogeissus leiocarpus* (DC.) Guill. & Perr., *Anthocleista nobilis* G.Don, *Borassus aethiopum* Mart., *Daniellia oliveri* (Rolfe) Hutch. & Dalziel, *Erythrophleum suaveolens* (Guill. & Perr.) Brenan, *Ficus sur* Forssk., *Gmelina arborea* Roxb. ex Sm., *Holarrhena floribunda* (G.Don) T.Durand & Schinz, *Khaya senegalensis* (Desv.) A.Juss., *Lannea acida* A.Rich., *Margaritaria discoidea* (Baill.) G.L.Webster, *Parkia biglobosa* (Jacq.) R.Br. ex G.Don, *Sterculia tragacantha* Lindl. and *Terminalia schimperiana* Hochst. ex Engl. & Diels. This overlap in species composition is expected, given that both protected areas are situated within the forest-savannah transition zone, which is characterized by similar climatic conditions and ecological dynamics (Veríssimo et al., 2024). The shared species reflect the adaptive strategies of woody plants thriving under transition zone conditions, where both forest and savannah species co-exist. Furthermore, several species identified in this study such as *Albizia ferruginea* (Guill. & Perr.) Benth., *Afzelia Africana* Sm. ex Pers., *Bridelia ferruginea* Benth., *Ceiba pentandra* (L.) Gaertn., *Ficus sur* Forssk., *Lecaniodiscus cupanioides* Planch., *Pouteria alnifolia* (Baker) Roberty, *Pterocarpus erinaceus* Poir. and *Sterculia tragacantha* Lindl. and *Trichilia prieureana* A.Juss. were also catalogued by Koulibaly et al. (2010) in Lamto Forest Reserve, Côte d'Ivoire, another forest-savannah transition ecosystem. This further supports the biogeographic and ecological similarities between transition zones in West Africa and underscores the importance of conserving these ecosystems to maintain regional biodiversity connectivity (Cardoso et al., 2016).

The Sørensen similarity coefficient was employed to evaluate the beta diversity between BFMS and KSNR. The result was 0.268 (26.8%), indicating that only 26.8% of the woody species are shared between the two sites, while the remaining 73.2% of species are unique to each site. This low similarity value suggests the need for site-specific conservation strategies, as each site harbours a unique set of species that contribute to regional biodiversity. Furthermore, the low SSC implies high beta diversity, meaning the species composition differs significantly between the sites. High beta diversity in forest-savannah transition zones has been widely documented (de Oliveira et al., 2023; Rees et al., 2023). For example, Vogel et al. (2024) and Lewis et al. (2023) reported that vegetation in such ecotones is highly heterogeneous due to variations in microclimate, soil properties, and disturbance regimes. Similarly, Rees et al. (2023) found that forest-savannah mosaics in Africa exhibit strong species turnover due to differing ecological pressures, such as fire frequency, soil fertility, and anthropogenic disturbances. The relatively low Sørensen similarity coefficient between BFMS and KSNR aligns with findings by Cardoso et al. (2021), who reported that woody species composition in the Central Africa transition zone varied significantly across different sites within the same transition ecosystem. These differences in species assemblages are often linked to local edaphic conditions and climatic gradients, as noted by Shenkin et al. (2020) in their study of transition zones in Brazil, Peru and Ghana.

4.1.4 Importance Value Index (IVI) of Woody Species

In addition to species abundance, the Importance Value Index (IVI) was employed as a metric to evaluate the ecological significance of the woody species identified in the study. The IVI provides a comprehensive assessment of species dominance by integrating relative density, relative frequency, and relative basal area (Mekonnen et al., 2023). Woody species with IVI of 10 and above were collated and presented in (Table 4.3). Among the species identified *Anogeissus leiocarpus* (DC.) Guill. & Perr. recorded the highest IVI in BFMS, while *Daniella Oliveri* (Rolfe) Hutch. & Dalziel had the highest *IVI* values in KSNR. A high IVI number indicates the species is abundant, widely distributed and occupies a significant portion of the ecosystem (Mekonnen et al., 2023), making it a substantial parameter in ecological and conservation assessments. The dominance of *Anogeissus leiocarpus* (DC.) Guill. & Perr. in BFMS and *Daniellia oliveri* (Rolfe) Hutch. & Dalziel in KSNR suggests that these species play pivotal roles in their respective ecosystems, influencing forest structure, resource availability and habitat suitability for other organisms. Their ecological importance highlights the need for sustained conservation efforts to maintain biodiversity and ecosystem stability.

Table 4.3: Woody species with a high IVI in the study area.

No.	Woody Species	IVI	Percentage (%)	Site
1.	*Anogeissus leiocarpus*	26.91	8.97	BFMS
2.	*Margaritaria discoidea*	21.87	7.29	BFMS
3.	*Cola gigantea*	21.65	7.21	BFMS
4.	*Holarrhena floribunda*	20.05	6.68	BFMS
5.	*Pouteria alnifolia*	13.20	4.40	BFMS
6.	*Gmelina arborea*	12.86	4.28	BFMS
7.	*Millettia zechiana*	10.28	3.43	BFMS
8.	*Daniellia oliveri*	54.75	18.25	KSNR
9.	*Pterocarpus erinaceus*	43.66	14.55	KSNR
10.	*Terminalia schimperiana*	33.28	11.09	KSNR
11.	*Sterculia tragacantha*	25.45	8.48	KSNR
12.	*Margaritaria discoidea*	27.14	9.05	KSNR
13.	*Lophira lanceolata*	18.43	6.14	KSNR
14.	*Lannea acida*	10.37	3.45	KSNR

4.2 Effects of anthropogenic activities on carbon stocks in BFMS and KSNR

Forests play a fundamental role in carbon storage and sequestration, serving as carbon sinks that mitigate climate change (Gogoi et al., 2022). However, anthropogenic activities such as agriculture, logging and infrastructure development have significantly altered forest ecosystems, leading to variations in carbon stocks across different landscapes (Leishangthem & Singh, 2018). In the Boabeng-Fiema Monkey Sanctuary (BFMS) and the Kogyae Strict Nature Reserve (KSNR), land use and land cover (LULC) changes over the past decades have influenced forest structure, biomass accumulation, and carbon sequestration potential. Understanding the extent to which human-induced disturbances affect carbon stocks is essential for designing effective conservation and management strategies. This section examined the effects of anthropogenic activities on carbon stocks in BFMS and KSNR, focusing on variations in carbon stock and density across different LULC classes, long-term carbon stock estimation trends from 1992 to 2023, and the decline in carbon stocks over this period. Furthermore, it explores the carbon sequestration potential of these ecosystems, providing insights into their capacity to recover from degradation and contribute to climate change mitigation. The findings from this analysis will be instrumental in informing sustainable forest management policies and conservation efforts aimed at preserving ecosystem functions and enhancing carbon storage in Ghana's protected areas.

4.2.1 Carbon Stock and Density across Land Use and Land Cover Classes

Forest ecosystems are the largest terrestrial carbon sink, playing a fundamental role in climate change mitigation. Carbon storage in forest ecosystems occurs across six primary carbon pools: aboveground, soil, belowground, litter, herbs (non-tree vegetation), and deadwood (Martin et al., 2021). This research focused on five of these pools: aboveground (AGC), Belowground (BGC), herbs, litter and soil organic carbon (SOC). Understanding the distribution of carbon stocks across these pools is essential for evaluating the contribution of different vegetation types to the global carbon cycle and developing targeted conservation strategies.

The estimation of carbon stocks across the various Land Use and Land Cover Classes (LULCC) within the study area: closed forest (CF), open forest (OF), woodland (WL), savannah (SV), and cropland (CL)—revealed that soil had the highest carbon stock among all the measured carbon pools (Figure 4.3). This finding aligns with previous research, which identifies soil as the largest terrestrial carbon reservoir and the need for sustainable land management and soil conservation practices to enhance carbon sequestration and mitigate climate change effects (Jackson et al., 2017). A comparative analysis of AGC and BGC across the different LULCCs revealed significant variations, suggesting that vegetation type substantially influences carbon storage capacity. The highest AGC and BGC values were recorded in closed forests, followed by open forests, woodland, savannah, and cropland. The high biomass carbon stocks in closed forests can be attributed to their dense tree cover, greater tree height, and higher basal area, which collectively contribute to increased carbon sequestration potential (Maure et al., 2023).

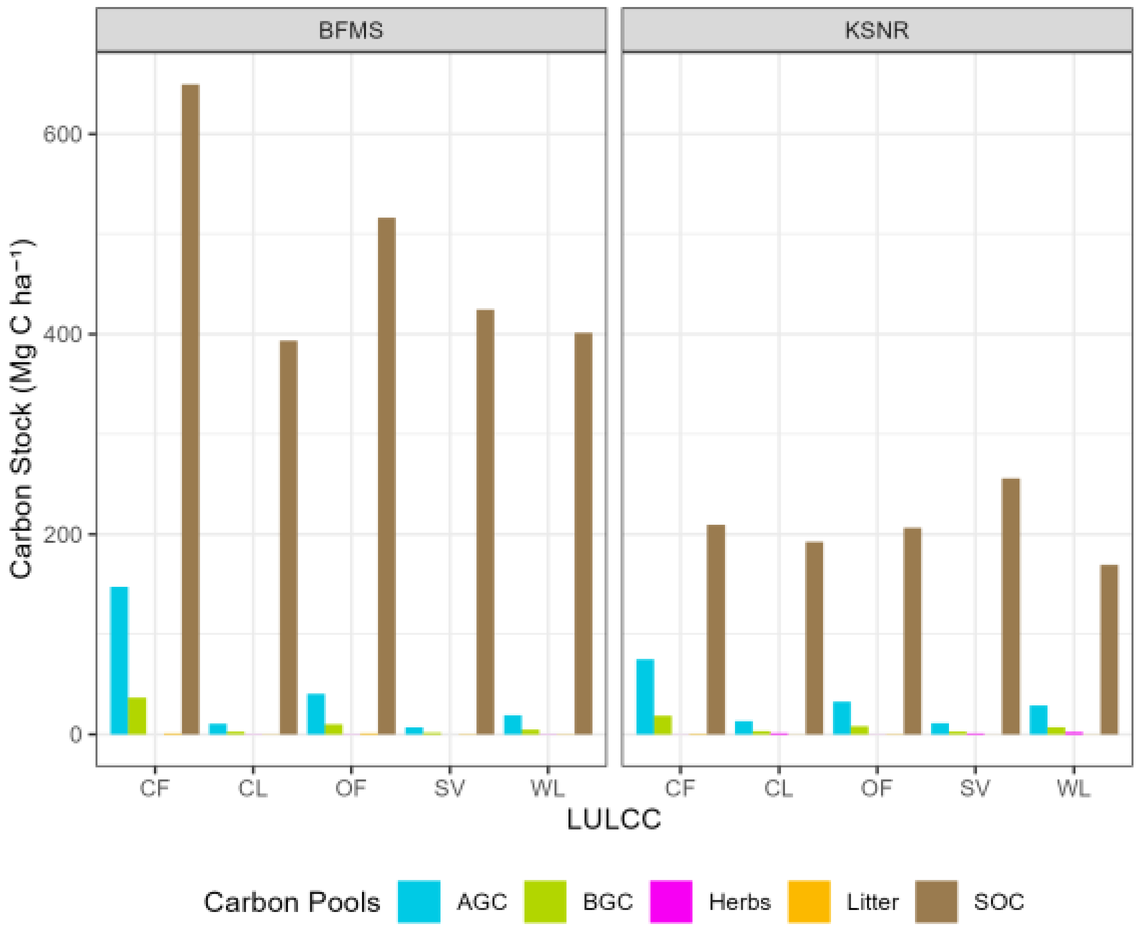

Figure 4.3: Carbon stock (Mg C ha-1) of the different carbon pools in the various LULCCs; BFMS and KSNR.

The closed forests had the highest carbon density in the study area (Figure 4.4). However, variations in carbon density across different vegetation types were observed between the two study sites: BFMS and KSNR. In BFMS, open forests had the second highest carbon density, followed by savannah, woodland, and cropland. This pattern suggests that open forests within BFMS retain a substantial amount of carbon, likely due to the presence of mature trees and relatively undisturbed soil conditions compared to other land cover types (Maracahipes-Santos et al., 2018). Conversely, in KSNR, savannah vegetation had the second highest carbon density, followed by open forest, cropland and woodland. Notably, the savannah vegetation in KSNR recorded the highest soil carbon stock, which significantly contributed to its overall carbon density. This divergence in carbon distribution between the two sites can be attributed to differences in ecological conditions, land-use histories, and vegetation structures.

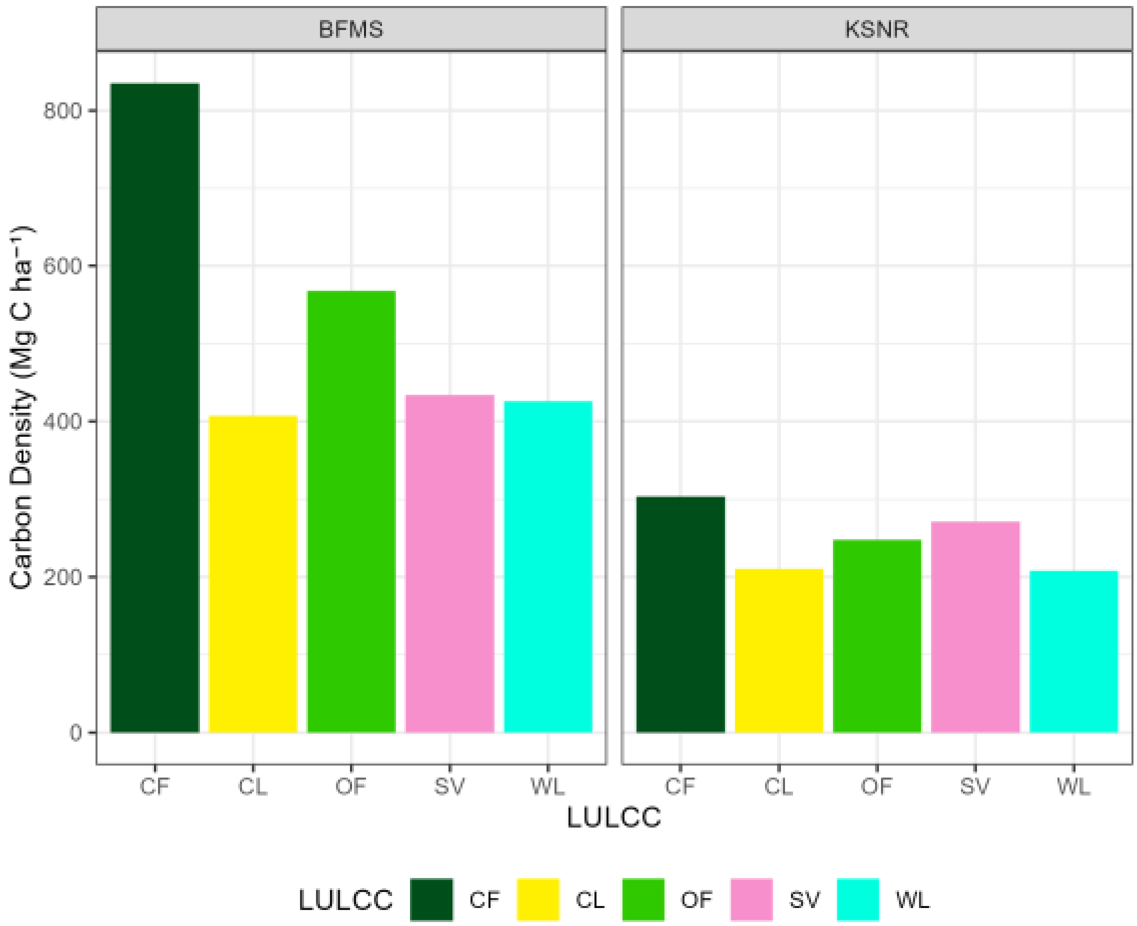

Figure 4.4: Carbon density (Mg C ha-1) of the different LULCC in BFMS and KSNR.

4.2.2 Carbon Stock Estimation from 1992 – 2023

The temporal analysis of land cover changes in BFMS and KSNR from 1992 to 2023 revealed distinct trends in forest cover dynamics and carbon stock variations. In BFMS, the area occupied by closed forests declined over the study period, while the extent of other land cover classes, including open forests, woodlands, savannah, and croplands, increased (Table 4.4). The historical land cover data for BFMS in 1992 and 2010 were adapted from Amankwah et al. (2021), providing a baseline for assessing long-term changes (Figure 4.5). The observed reduction in closed forests within BFMS can be attributed to factors such as anthropogenic disturbances, agricultural expansion, and shifting land-use patterns, all of which contribute to the loss of carbon-rich forest ecosystems (Amankwah et al., 2021; Janssen et al., 2018).

In contrast, KSNR exhibited a different trajectory of land cover change, with both open forests and closed forests declining over the same period (Figure 4.6). Notably, the loss of forest cover in KSNR was accompanied by an expansion of built-up areas and bare lands, indicating increased human encroachment and land conversion. Additionally, a significant portion of open forests in KSNR transitioned into woodlands, reflecting shifts in vegetation structure and composition. This transformation suggests a gradual degradation of forested landscapes, likely driven by anthropogenic pressures such as logging, firewood extraction, and grazing activities (Nogueira et al., 2018).

To evaluate the reliability of the classification results, an accuracy assessment was conducted using standard validation indices including Producer's Accuracy, User's Accuracy and Kappa Statistics, which are key measures of classification performance (Crowley, 2024; Li et al., 2023). Table 4.5 presents the Producer's Accuracy and Kappa Statistics. The results from the Overall Classification Accuracy and Overall Kappa Statistic indicate a substantial level of agreement between the reference data and the classified map. These indices validate the classification process and provide a measure of its reliability for further analysis (see Appendix 5 for detailed tables).

Table 4.4: Spatial Extent of the different LULCC in hectares.

LULCC	**BFMS**			**KSNR**		
	1992	2010	2023	1992	2010	2023
Closed Forest	370	205	40	4225	3700	2277
Open Forest	31	133	206	10949	5854	8441
Woodland	26	27	81	4879	7732	4439
Savannah	41	33	64	4938	4093	3660
Cropland	28	46	29	4971	3790	3702
Built-up/Bare lands	40	92	103	2908	7707	10358

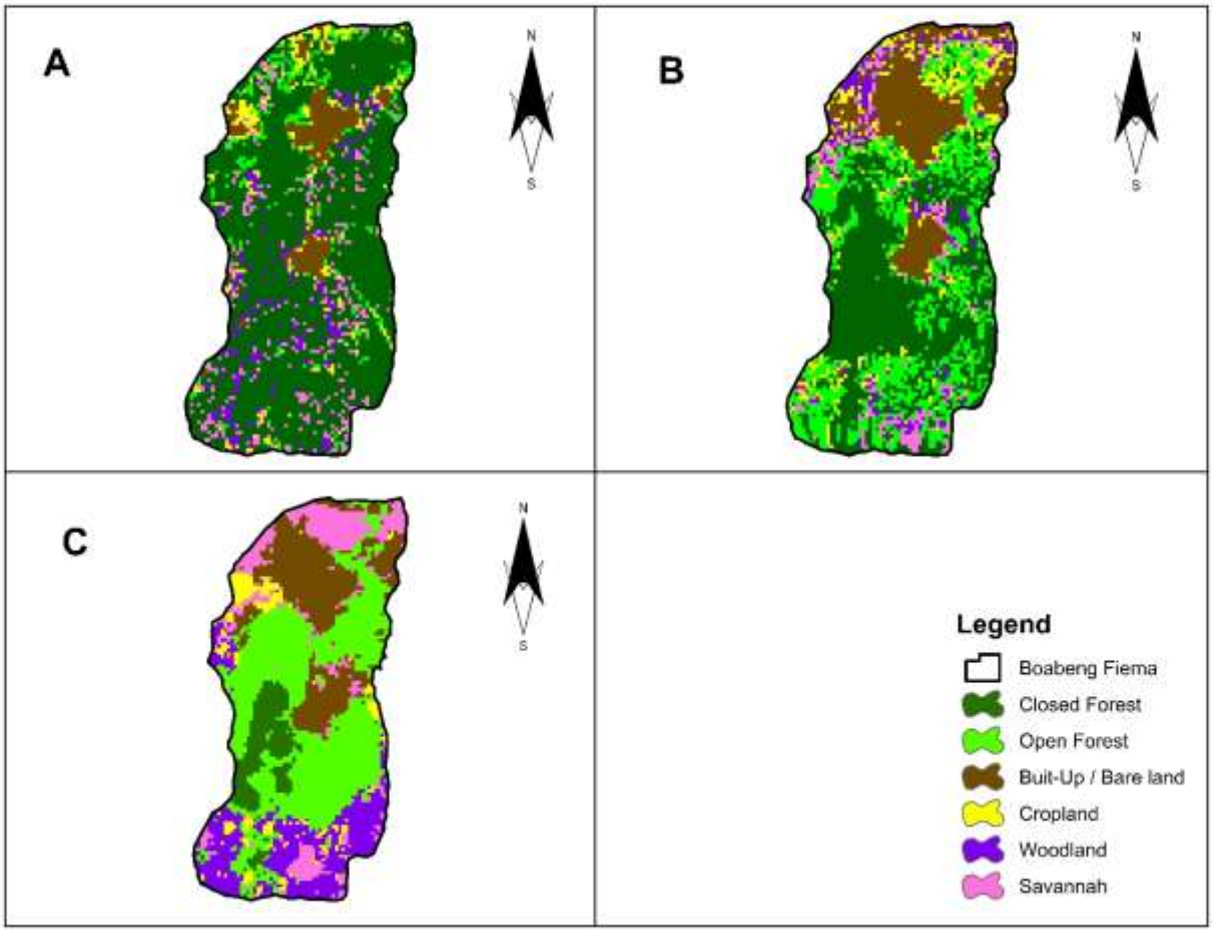

Figure 4.5: Classified map of BFMS in three stages: (A)1992, (B) 2010 and (C) 2023.

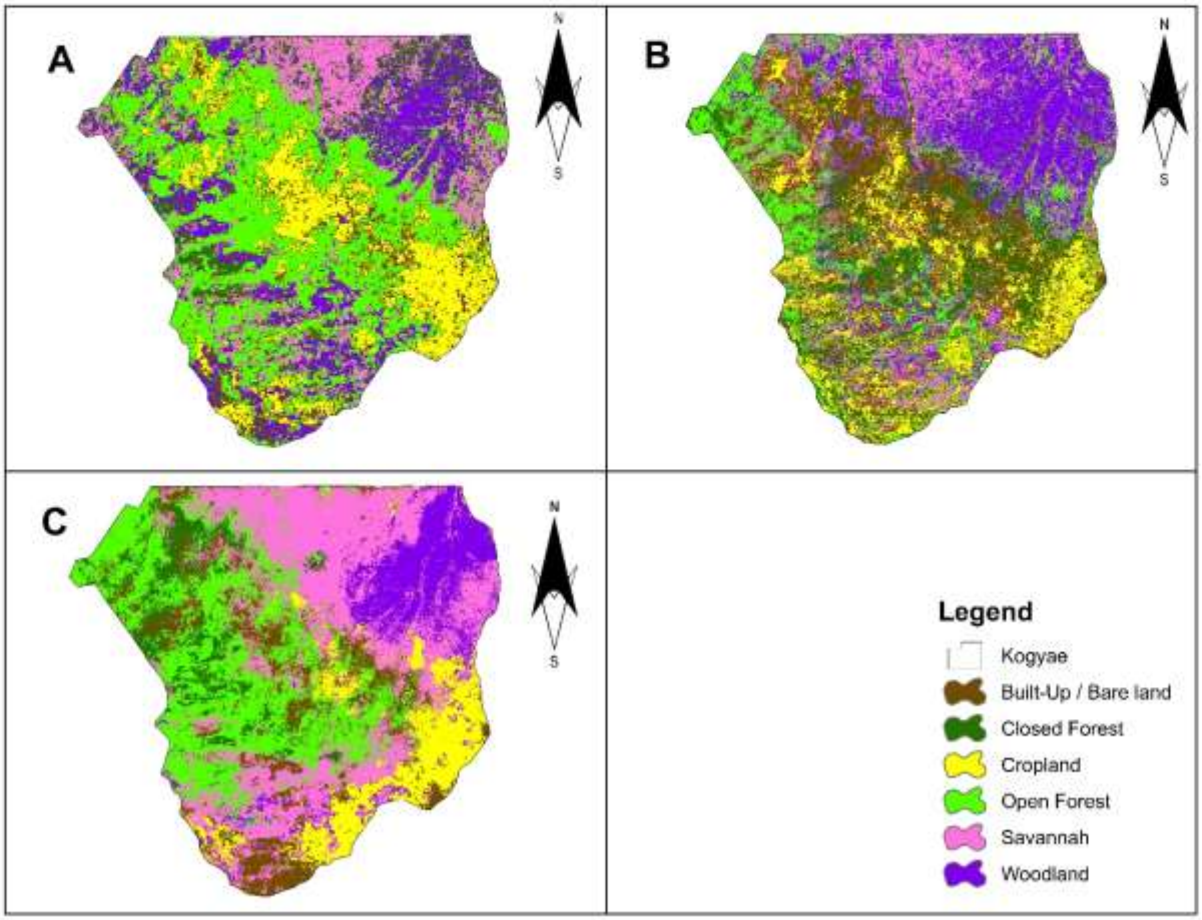

Figure 4.6: Classified map of KSNR in three stages: (A)1992, (B) 2010 and (C) 2023.

Table 4.5: Accuracy Assessment of Land Use Land Cover Classification

Validation Indices	BFMS			KSNR		
	1992	2010	2023	1992	2010	2023
Overall Classification Accuracy (%)	75	85	88	73	82	86
Overall Kappa Statistics	0.72	0.80	0.82	0.71	0.78	0.81

4.2.3 Carbon Stock Decline from 1992 to 2023

The overall carbon stock in the study area declined significantly between 1992 and 2023, reflecting the impacts of deforestation and land-use changes on carbon sequestration. BFMS experienced a total carbon loss of 40,236 Mg C, while KSNR recorded a much more substantial reduction of 272,109 Mg C (Table 4.6). This decline is in contrast to the objectives outlined in Ghana's National Climate Policy (NCCP), which prioritises increasing carbon sinks and minimising greenhouse gas emissions to support climate change mitigation efforts (MESTI, 2013). The continued loss of carbon stocks in these ecologically significant landscapes underscores the urgent need for targeted conservation and restoration strategies to reverse these trends. Moreover, carbon depletion contributes to climate change, global warming, and associated environmental and socio-economic challenges (Yoro & Daramola, 2020).

Within BFMS, the most substantial reduction in carbon stock occurred between 2010-2023, with a recorded loss of 20,282 Mg C. This aligns with the findings of Amankwah et al. (2021), who identified deforestation and forest degradation as major contributors to carbon stock decline. These changes are primarily driven by anthropogenic activities such as farming, illegal tree felling, and charcoal production, which were prevalent between 1992 and 2018 and contributed significantly to the sanctuary's declining carbon stock. In contrast, KSNR experienced its most severe reduction in carbon stock between 1992 and 2010, losing 148,871 Mg C during this period. This substantial decrease aligns with findings by Janssen et al. (2018), who reported an alarming rise in deforestation rates within KSNR due to increasing human pressures. Hunting, agricultural expansion, and other land conversion activities drove deforestation rates from 1.7% to 5.4%, resulting in a dramatic decline in forest cover and carbon sequestration potential. The intensified deforestation and habitat degradation during this period reflect the significant carbon stock losses observed in the reserve. However, from 2010 to 2023, KSNR exhibited a noticeable reduction in carbon loss, suggesting a shift toward ecosystem recovery. Janssen et al. (2018) reported a recovery phase of the reserve within the same period. Although the overall carbon stock continues to decline, the slowed rate of carbon loss in recent years highlights the potential for forest regeneration and improved carbon sequestration under effective conservation policies.

Table 4.6: Aboveground Carbon (AGC) stock (Mg C) of the study area from 1992 to 2023.

Given Year	BFMS	KSNR
1992	56,827	938,865
2010	36,873	789,994
2023	16,592	666,756
Carbon loss 1992-2010	-19,954	-148,871
Carbon loss 2010-2023	-20,282	-123,238
Carbon loss 1992-2023	-40,236	-272,109

4.2.4 Carbon Sequestration Potential

The assessment of carbon sequestration potential using carbon dioxide equivalent (CO_2e) facilitated an evaluation of the role of protected areas in climate change mitigation. The sequestration capacity of different vegetation types (Table 4.7) highlights their contribution to reducing atmospheric CO_2 levels and mitigating climate change. Within the framework of Reducing Emissions from Deforestation and Forest Degradation (REDD+), the conservation of forest carbon stocks, sustainable forest management, and the enhancement of forest carbon reserves are key strategies for mitigating emissions (Minang & Murphy, 2010).

Beyond carbon sequestration, the forests of BFMS provide multiple ecological and socio-economic benefits. The sanctuary serves as a habitat and food source for primates, supporting species conservation while also functioning as an eco-tourism site that fosters cultural heritage and generates local economic benefits (Amankwah et al., 2021; Kankam et al., 2023). Such multifunctional roles enhance the overall resilience of the protected area, contributing to both biodiversity conservation and sustainable development. Furthermore, the forests of both KSNR and BFMS, characteristic of the forest-savannah transition zone, are rich in trees that play a crucial role in stabilizing ecosystem processes. Biodiversity within these ecosystems serves as a buffer against climate extremes, reinforcing ecological resilience by enhancing carbon sequestration, ecosystem services and ecosystem functionality (X. Chen et al., 2023; Hisano et al., 2018; Ray et al., 2023). A fundamental approach to addressing climate change lies in the application of NbS and these two protected areas can serve as practical solutions for climate change mitigation. Their combined roles in carbon sequestration, biodiversity conservation, and ecosystem service provision underscore their significance as natural climate solutions. Effective conservation policies, coupled with sustainable forest management, can further enhance their capacity to act as long-term carbon sinks while preserving biodiversity and supporting local livelihoods.

Table 4.7: Carbon sequestration potential (Mg C ha-1) of the different LULLC.

LULCC	**BFMS**		**KSNR**	
	Carbon Density	Carbon Sequestration Potential	Carbon Density	Carbon Sequestration Potential
CF	835	3,063	304	1,115
OF	568	2,086	248	910
WL	426	1,563	208	764
SV	434	1,593	271	996
CL	407	1,494	211	773

Carbon density refers to the total amount of carbon stored within an ecosystem, expressed as the sum of all carbon stocks across different carbon pools (e.g., aboveground biomass, belowground biomass, litter, herbs and soil organic carbon). Carbon sequestration potential is the amount of carbon dioxide (CO_2) that can be removed from the atmosphere and stored in biomass and soils. It is estimated by multiplying carbon density by 3.67, which represents the molecular weight ratio of CO_2 (44 g/mol) to carbon (12 g/mol).

4.3 Influence of Soil Physicochemical Properties on Woody Species Abundance

Soil physicochemical properties play a fundamental role in shaping vegetation structure, species abundance and overall ecosystem dynamics (Hofhansl et al., 2020). In forest-savannah transition zones, variations in soil nutrients, pH, organic matter content and bulk density influence the establishment, growth, abundance and distribution of woody species (Dodoo et al., 2023).

Understanding these soil-vegetation interactions is essential for assessing ecosystem resilience, biodiversity conservation, and land management strategies. This section discusses the influence of soil physicochemical properties on woody species abundance in BFMS and KSNR. It explores how variations in key soil parameters contribute to species assemblages across different land use and land cover types. Additionally, the section highlights the key soil physicochemical properties that significantly shape species distribution patterns in the two reserves, providing insights into the ecological processes governing forest and savannah landscapes.

The CCA biplots illustrate the influence of soil properties on woody species abundance along the first two constrained axes (CCA1 and CCA2). B.S., pH, and Na exhibited strong positive associations with these axes in BFMS and KSNR, indicating that these soil properties substantially influence woody species abundance in the study area (Figure 4.7 and Figure 4.8). These findings are consistent with previous studies emphasising the role of soil nutrients and physicochemical properties in driving vegetation patterns and composition (Adu-Bredu et al., 2021; Hofhansl et al., 2020; Jolokhava et al., 2021).

In BFMS, B.D had a negative loading on the CCA plot. However, a high number of woody species were clustered around it, suggesting that these species may possess adaptations enabling them to tolerate higher soil compaction. This aligns with previous findings indicating that certain woody species develop morphological or physiological mechanisms to cope with compacted soils (Jourgholami et al., 2016). Alameda & Villar (2012) further demonstrated that soil compaction alters root anatomy and morphology, influencing plant growth. Furthermore, studies have shown that tree species in dryland and savannah ecosystems often develop specialised root structures to navigate dense soils and access deeper water reserves (Paz et al., 2015; Tölgyesi et al., 2023; Zhou et al., 2019).

Permutation tests identified T.N and pH as the most significant drivers of species abundance in BFMS and Na as the key factor in KSNR ($p < 0.05$). Nonetheless, the CCA results indicated that B.D, B.S, pH and Na also play important roles in shaping species abundance within these protected areas. Collectively, these results indicate that B.D, B.S, Na, pH and T.N influence woody species abundance in the protected areas. These findings align with ecological studies indicating that soil nutrients and pH are major drivers of plant community structure (Awoonor, 2012; Yaseen et al., 2022).

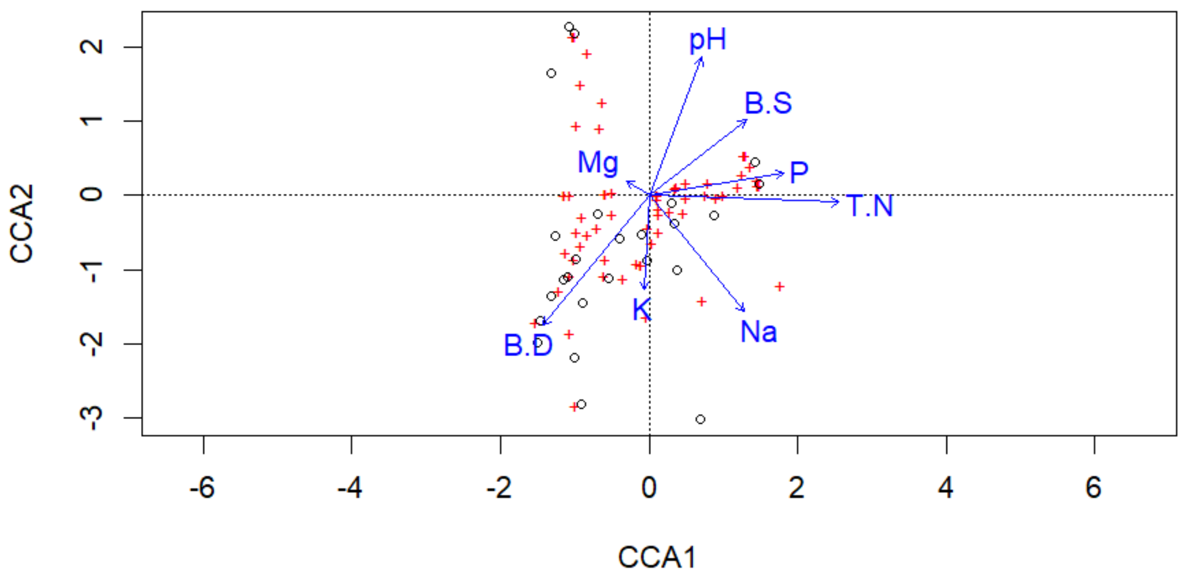

Figure 4.7: Canonical correspondence analysis (CCA) biplot ordination between soil physicochemical properties and woody species abundance in BFMS.

Arrows (blue vectors) represent the soil variables (environmental factors). Their direction shows the gradient along which species respond. Species (red + signs) are plotted according to their weighted averages concerning the soil properties. Sites (black circles) represent the locations in the ordination space.

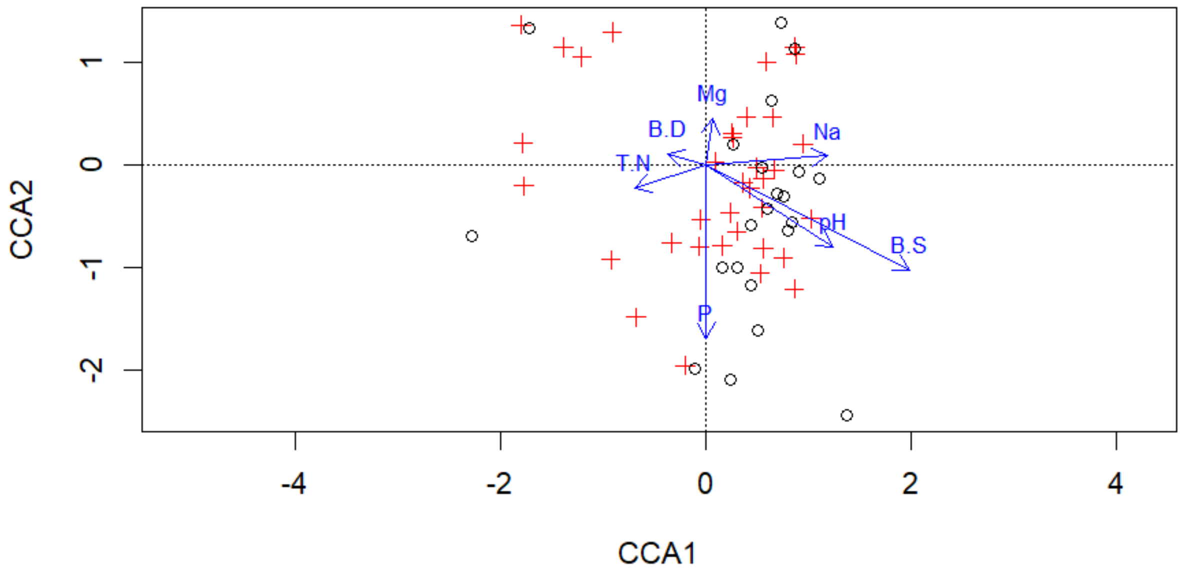

Figure 4.8: Canonical correspondence analysis (CCA) biplot ordination between soil physicochemical properties and woody species abundance in KSNR.

The results from the partitioning of variance revealed that 40.27% of the variation in BFMS and 34.41% in KSNR (Figure 4.9) is attributed to soil properties. These findings underscore the significant impact of the soil physicochemical properties on woody species abundance, aligning with previous studies that emphasize the role of soil conditions in shaping vegetation structure and diversity. Several studies have demonstrated that soil nutrient availability is a key determinant of plant species distribution, richness, abundance and composition across various ecosystems. Mensah et al. (2023), Sellan et al. (2019) and Veríssimo et al. (2024) corroborated that soil properties such as nutrient content, pH, and bulk density play fundamental roles in species establishment and competition, particularly in transition zones where edaphic factors mediate vegetation dynamics.

While this study highlights the strong correlation between soil physicochemical properties and woody species abundance, it is noteworthy that other biotic and abiotic factors also influence vegetation patterns. Previous research suggests that topographical variation, anthropogenic activities, climate variability and fire events exert significant influence on plant community dynamics (Adu-Bredu et al., 2021; Thakur et al., 2022). For instance, terrain features such as slope and elevation can create microhabitats with distinct soil moisture and nutrient regimes, thereby affecting species establishment and distribution (Boakye et al., 2017). Additionally, climate-driven factors, including precipitation variability and temperature fluctuations, influence soil water availability and nutrient cycling, further shaping vegetation structure in the transition zone (Aguirre-Gutiérrez et al., 2020).

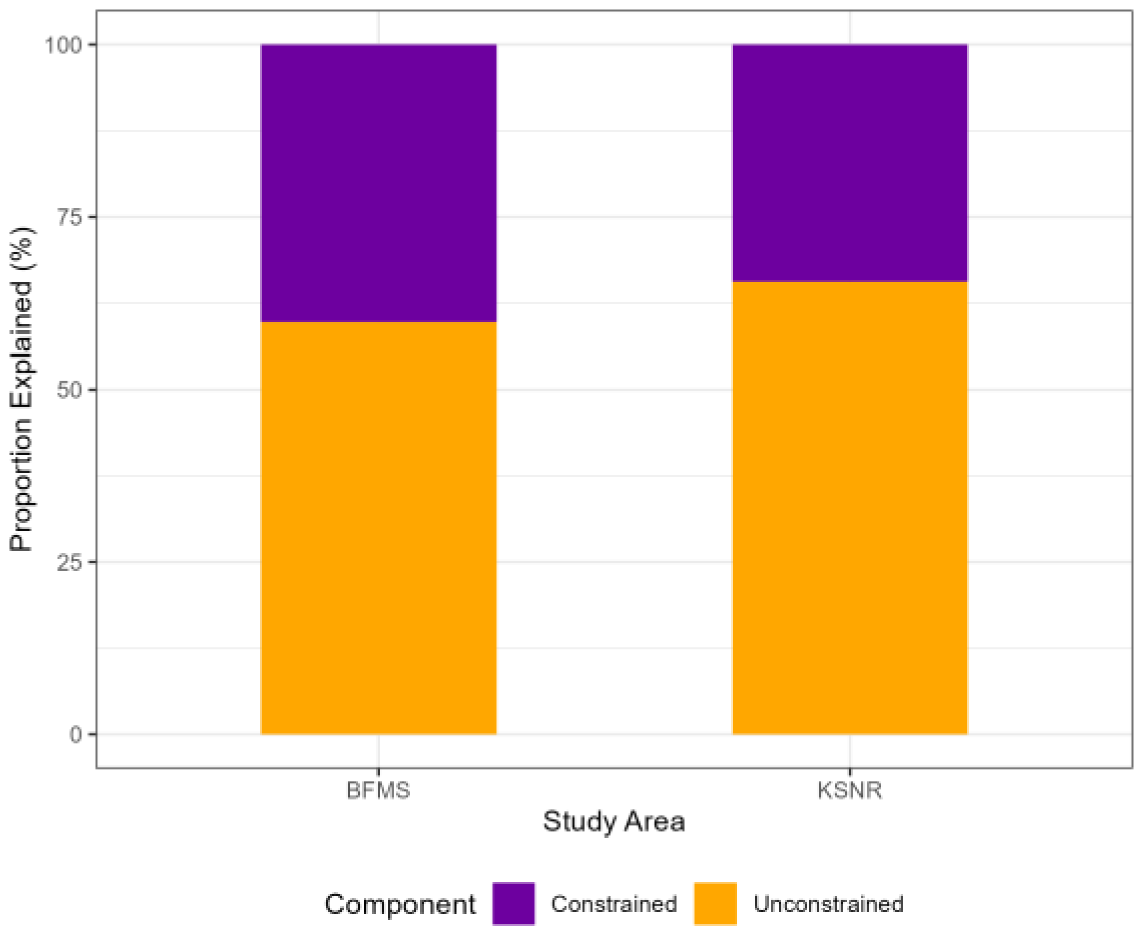

Figure 4.9: Proportion of variation in woody species abundance explained by soil physicochemical properties in BFMS and KNSR.

4.4 Conservation Status of the Protected Areas

Protected areas play a crucial role in biodiversity conservation by safeguarding ecologically significant habitats and species. Assessing their conservation status provides valuable insights into their effectiveness in preserving biodiversity at both national and international levels. In this study, the Genetic Heat Index (GHI) and Red List Index (RLI) were employed to evaluate the 'bioquality' of the protected areas, providing a numerical score to assess their conservation statuses. This section discusses the conservation status of the protected areas, focusing on their ecological significance, species composition and overall conservation value. The assessment includes an analysis of the national and international conservation status and star rating of woody species, highlighting the importance of these areas in maintaining biodiversity and mitigating species loss.

4.4.1 Genetic Heat Index of the Protected Areas

Each species was categorised into a star rating based on its rarity at both national and international levels, degree of endemism and ecological and taxonomic characteristics (Figure 4.10). This classification formed the basis for calculating the Genetic Habitat Index (GHI), a metric that quantifies the conservation value of an area by integrating species presence, rarity and endemism.

As illustrated in Figure 4.10, the study sites harbour ecologically important woody species, including those with low occurrence nationally and internationally, as well as species under pressure from exploitation. This is evidenced by the presence of gold, pink, red and scarlet-rated species (Hawthorne & Abu-Juam, 1995; Hawthorne & Gyakari, 2006). Such findings underscores the significance of these protected areas within national conservation strategies, particularly in regions experiencing increasing anthropogenic pressure such as agricultural expansion, illegal logging and land-use change.

The GHI values recorded for BFMS and KSNR are 134.24 and 105.41, respectively. According to the categorisation of GHI by Owusu-Prempeh et al. (2018), these values suggest the study area supports a rich and ecologically important assemblage of woody species, emphasising its role in biodiversity conservation. Furthermore, the GHI values are consistent with the designation of BFMS and KSNR as key biodiversity areas and strengthen the case for increased investment in their management and ecological restoration (Oduro et al., 2012). In this regard, BFMS and KSNR contribute not only to local biodiversity conservation but also support Ghana's commitments under international frameworks such as the Convention on Biological Diversity (CBD) and Reducing Emissions from Deforestation and Forest Degradation + conservation, sustainable management of forests, and enhancement of forest carbon stocks (REDD+) (Ghana Forestry Commission, 2017). Effective management interventions should prioritise the protection of species of high conservation concern, restoration of degraded habitats and mitigation of anthropogenic threats such as deforestation and habitat fragmentation. In addition, long-term monitoring is vital to track changes in species composition and ensure the continued effectiveness of conservation strategies remain effective (Hábová et al., 2019).

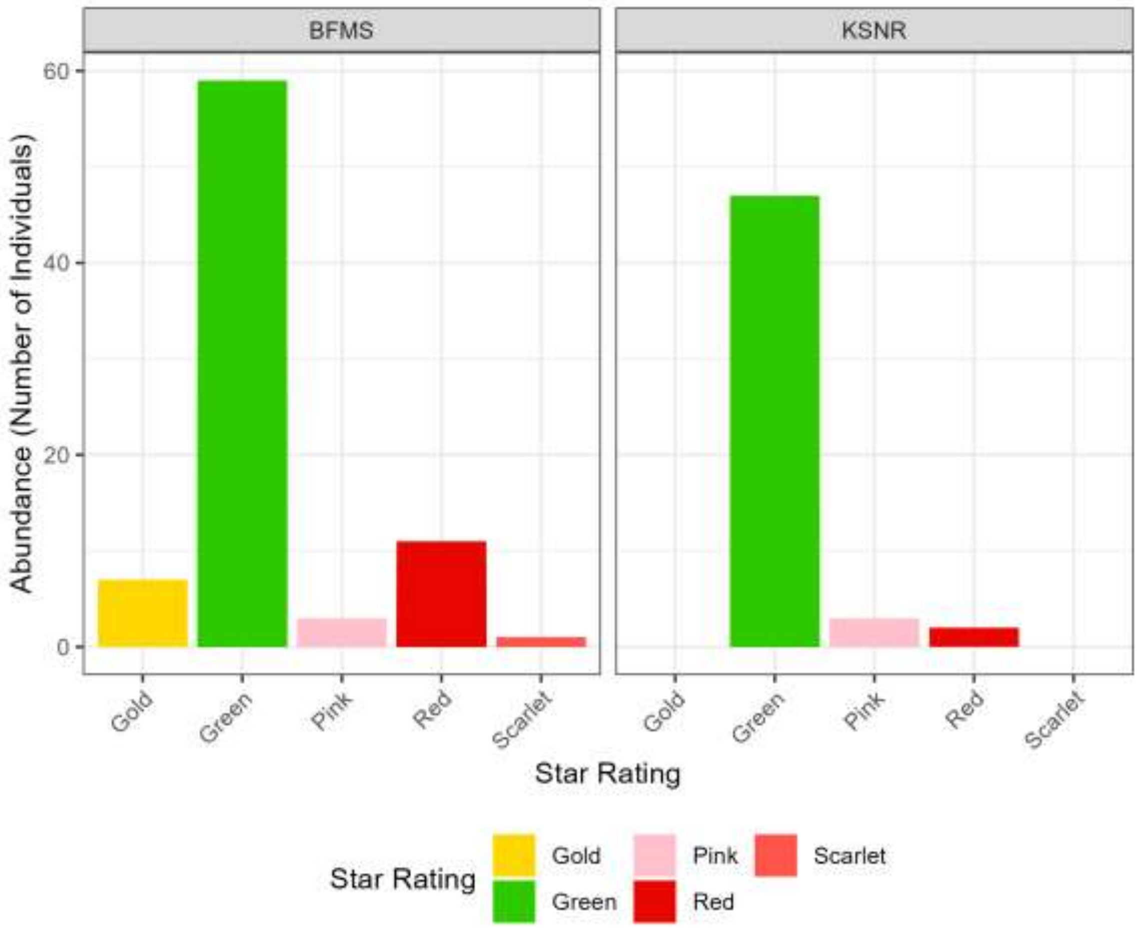

Figure 4.10: Star rating of woody species in the protected areas.

4.4.2 IUCN Ranking of Woody Species in the Protected Areas

The vegetation of BFMS and KSNR provides habitats for woody species ranked as near threatened, vulnerable and endangered on the International Union for Conservation of Nature (IUCN) Red List (IUCN, 2023) (Table 4.8). These woody species are of high economic value, heavily exploited for timber and traded internationally (Bandoh et al., 2016). Their extraction poses a significant threat to biodiversity. *Vitellaria paradoxa* C.F.Gaertn., listed as vulnerable on the Red List, is identified as the second most significant oil crop in Africa and the primary source of vegetable oil in rural areas of the savannah zone of West Africa, thereby contributing significantly to livelihoods and culture (Nguekeng et al., 2021). The presence of such species emphasises the ecological importance of the study area for the conservation of biodiversity at both local and global scales. Furthermore, there is increasing evidence that biodiversity conservation contributes significantly to climate change mitigation and adaption by sequestering large amounts of greenhouse gases from the atmosphere along with improving ecosystem services, functioning and resilience (Amankwah et al., 2024; Chen et al., 2023; Isbell et al., 2015; Ouyang et al., 2021; Rees et al., 2023). Woody species that had not been evaluated by the IUCN Red List (IUCN, 2023) were excluded from the ranking analysis. However, the presence of non-evaluated species is acknowledged, and further assessments, such as national or regional conservation listings, could provide additional insights into their status.

Table 4.8: Rating of woody species by IUCN.

No.	Species	IUCN Rating	Site
1.	*Afzelia africana*	Vulnerable	BFMS and KSNR
2.	*Albizia ferruginea*	Near threatened	BFMS
3.	*Antrocaryon micraster*	Vulnerable	BFMS
4.	*Entandrophragma candollei*	Vulnerable	BFMS
5.	*Khaya grandifoliola*	Vulnerable	BFMS
6.	*Khaya senegalensis*	Vulnerable	BFMS and KSNR
7.	*Lophira alata*	Vulnerable	BFMS
8.	*Milicia excelsa*	Near threatened	BFMS
9.	*Nesogordonia papaverifera*	Vulnerable	BFMS
10.	*Pterocarpus erinaceus*	Endangered	KSNR
11.	*Vitellaria paradoxa*	Vulnerable	KSNR

Figure 4.11 presents the distribution of woody species across IUCN conservation categories, which were used in the calculation of the RLI value. The abundance of species in each category informs the RLI value as higher proportions of endangered and vulnerable species contribute to lower RLI scores. While RLI provides a single metric for assessing extinction risk, this figure offers a detailed breakdown of species distribution, providing ecological context for the calculated RLI values. The RLI values of BFMS and KSNR are 0.21 and -1.55 respectively. The low RLI value of BFMS suggests the sanctuary has species at a high risk of extinction and the need for biodiversity conservation and restoration efforts. *Pterocarpus erinaceus* Poir. rated as an endangered species on the IUCN Red List, is the most abundant woody species in KSNR (Figure 4.2). The prevalence of *P. erinaceaus* contributed to KSNR's negative RLI value. *P. erinaceaus* is one of the most heavily exploited tree species in West Africa. Approximately, 80% of Rosewood traded worldwide

comes from West Africa (Baidoo et al., 2023). In March 2019, the Ministry of Lands and Natural Resources of the Government of Ghana placed a complete ban on the harvesting and trade of *P. erinaceaus* (Kansanga et al., 2021). However, illegal exploitations persist, posing a serious challenge to the recovery of the species (Kansanga et al., 2021). The negative RLI value recorded for Kogyae thus reflects the presence of highly threatened species, particularly *P. erinaceus*, and highlights the urgent need for strengthened conservation efforts and measures to prevent further biodiversity loss.

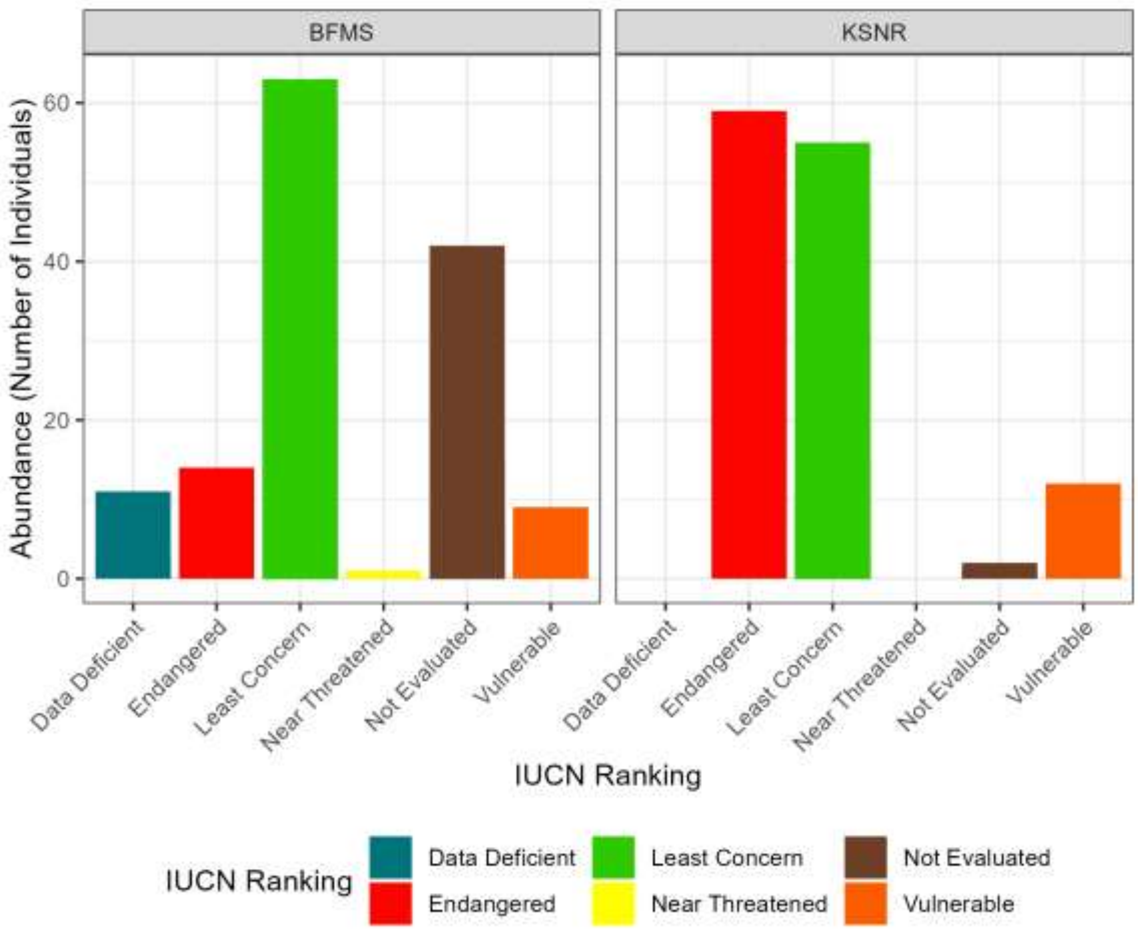

Figure 4.11: IUCN ranking of woody species in the protected areas.

4.5 Insights into Forest Conservation Practices from the Perspectives of the Inhabitants of BFMS and KSNR

Local communities play a major role in forest conservation, as their knowledge, perceptions, and practices directly influence ecosystem sustainability (Sobeng et al., 2023). Understanding how inhabitants of protected areas interact with their environment provides valuable insights into conservation efforts, challenges, and potential interventions. Socio-demographic factors such as age, education, occupation and cultural beliefs can shape individuals' awareness and engagement in conservation practices, ultimately affecting the effectiveness of management strategies (Ito & Kawazoe, 2018; Tamene et al., 2024; Zoderer et al., 2016).

This section explores forest conservation practices from the perspectives of the inhabitants of BFMS and KSNR. It examined the socio-demographic characteristics of respondents, identified key conservation practices from the perspectives of the local communities and assessed how socio-demographic factors influenced conservation practices. The findings provide important perspectives on integrating local knowledge into sustainable conservation policies and fostering community-driven forest management approaches.

4.5.1 Socio-demographic Characteristics of Respondents

The socio-demographic variables of the respondents in this study provide valuable insights into the demographic and socio-cultural factors of BFMS and KSNR. The study revealed a notable gender disparity, with more male respondents than female respondents in both study areas (Figure 4.12). This finding aligns with broader socio-cultural norms prevalent in many rural communities in Ghana, where traditional gender roles often shape individuals' engagement in social, economic, and environmental affairs (Figueroa et al., 2023). Women, particularly in rural areas, tend to bear significant household and caregiving responsibilities, limiting their ability to participate in conservation-related activities that require time away from domestic duties (Afriyie et al., 2021a).

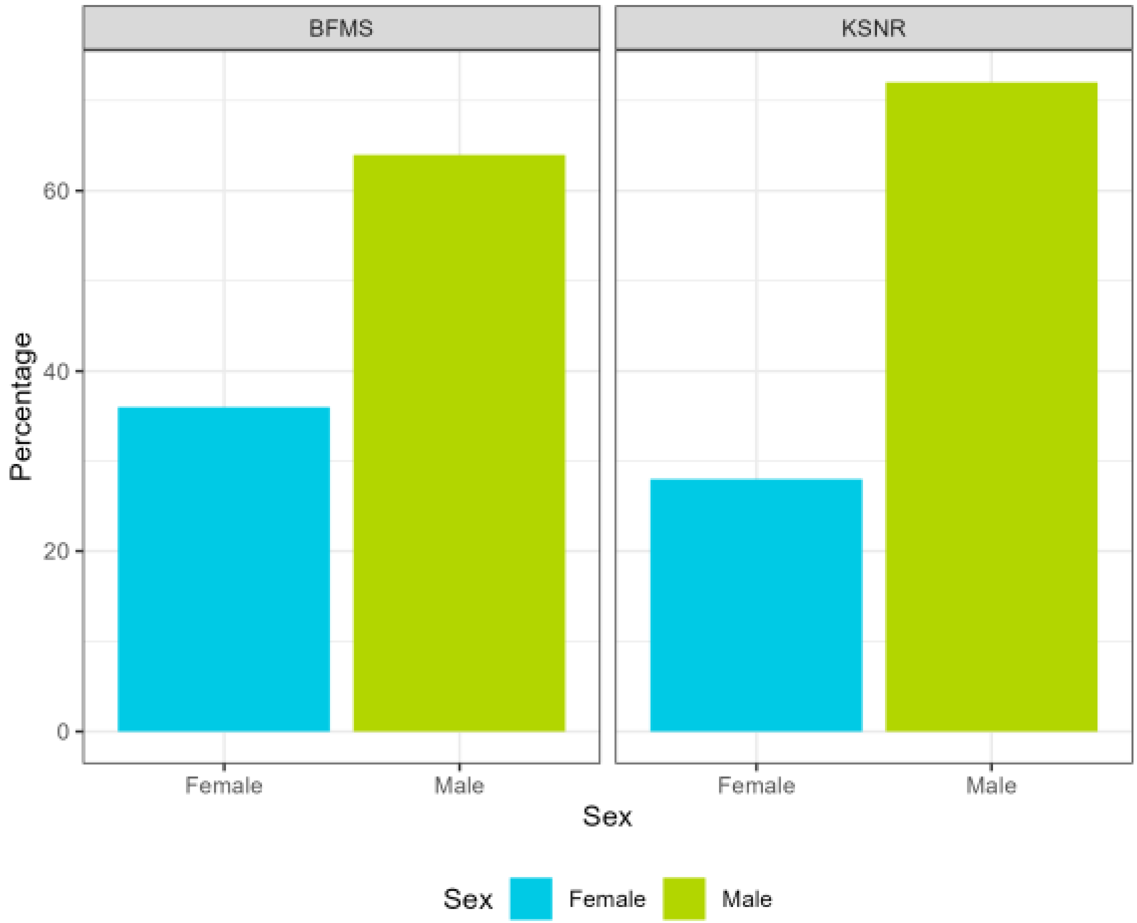

Figure 4.12: Sex distribution of respondents in BFMS and KSNR.

The age distribution of respondents showed a predominance of individuals above 50 years, with a notable number of respondents in the 20-30 years age range (Figure 4.13). This pattern may reflect cultural norms in many African communities, where older individuals—often regarded as household heads—are more likely to participate in interviews (Randall & Coast, 2016). As the study did not explicitly assess the presence or number of younger adults (18 years and above) within these households, the findings do not provide sufficient evidence to conclude that the community is predominantly composed of older individuals.

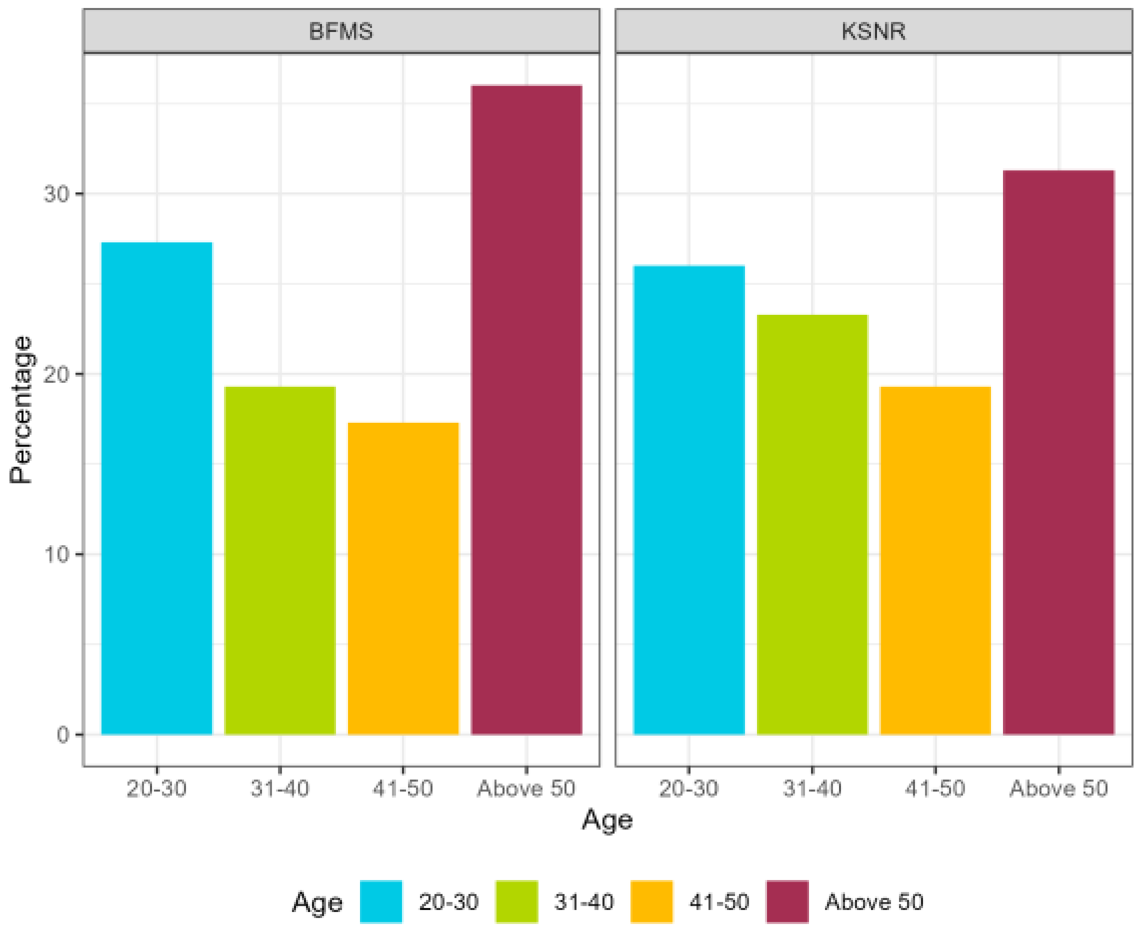

Figure 4.13: Age group distribution of respondents in BFMS and KSNR.

Educational levels varied between the two study sites. In KSNR, a higher proportion of respondents were uneducated compared to those in BFMS (Figure 4.14). However, the majority of respondents in both areas had a Junior High School (middle school). The finding from KSNR regarding the relatively low educational level corroborates the research of Oduro-Ofori et al. (2015), which noted the educational challenges faced by the communities in the area.

While lower formal education levels may suggest limited access to structured environmental education, they do not necessarily correlate with a lack of knowledge about conservation practices. In many rural and traditional communities, local knowledge systems passed down through generations, can provide a strong foundation for understanding and engaging in sustainable land use and conservation practices (Cebrián-Piqueras et al., 2020). For example, community-based conservation efforts, often grounded in indigenous knowledge, can shape local perspectives on forest management, irrespective of formal education levels (Sinthumule & Mashau, 2020). Existing literature supports the view that traditional ecological knowledge, particularly in rural areas, can significantly influence conservation behaviors, even when formal education is limited (Boafo et al., 2016; Dreoni et al., 2022).

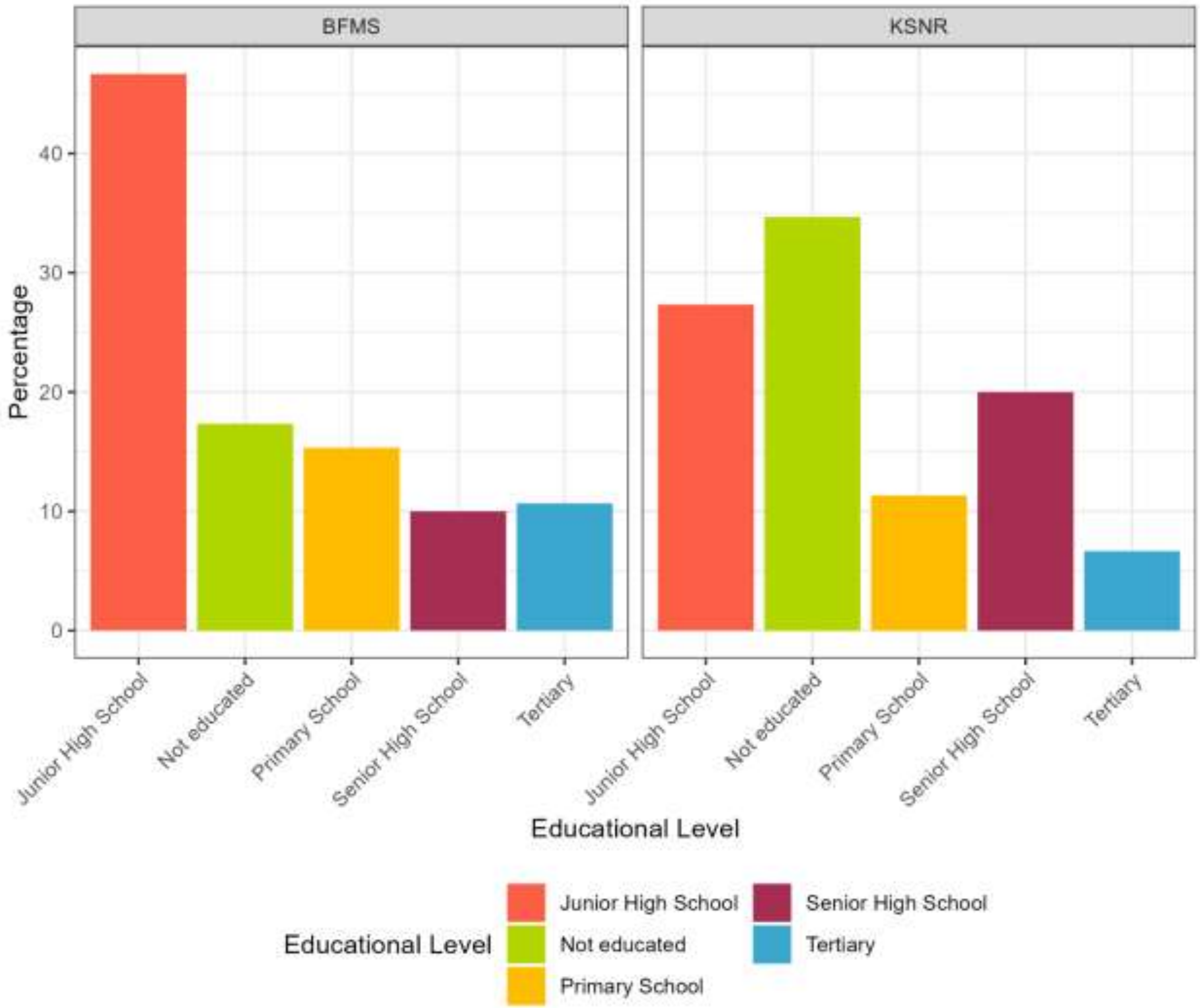

Figure 4.14: Educational level of respondents in BFMS and KSNR.

Farming emerged as the primary occupation in both communities, with 60% of respondents in BFMS and 79% of respondents in KSNR identifying as farmers (Figure 4.15). This is consistent with the fact that the forest-savannah transition zone is the agricultural hub of many Sub-Saharan African countries, including Ghana (Staver et al., 2011). Additionally, Ayivor et al. (2020) reported that 89% of the respondents they interviewed in KSNR were farmers, further reinforcing the centrality of agriculture to the livelihoods of these communities. The crops grown in the study area include maize, yam, rice and cassava in BFMS, while yam and groundnut cultivation dominate KSNR. These agricultural activities are likely to affect the surrounding forests, especially through practices like slash-and-burn agriculture, which contribute to deforestation and forest degradation. Livestock rearing was also observed in both sites, along with other economic activities such as palm wine tapping and cattle rearing in KSNR.

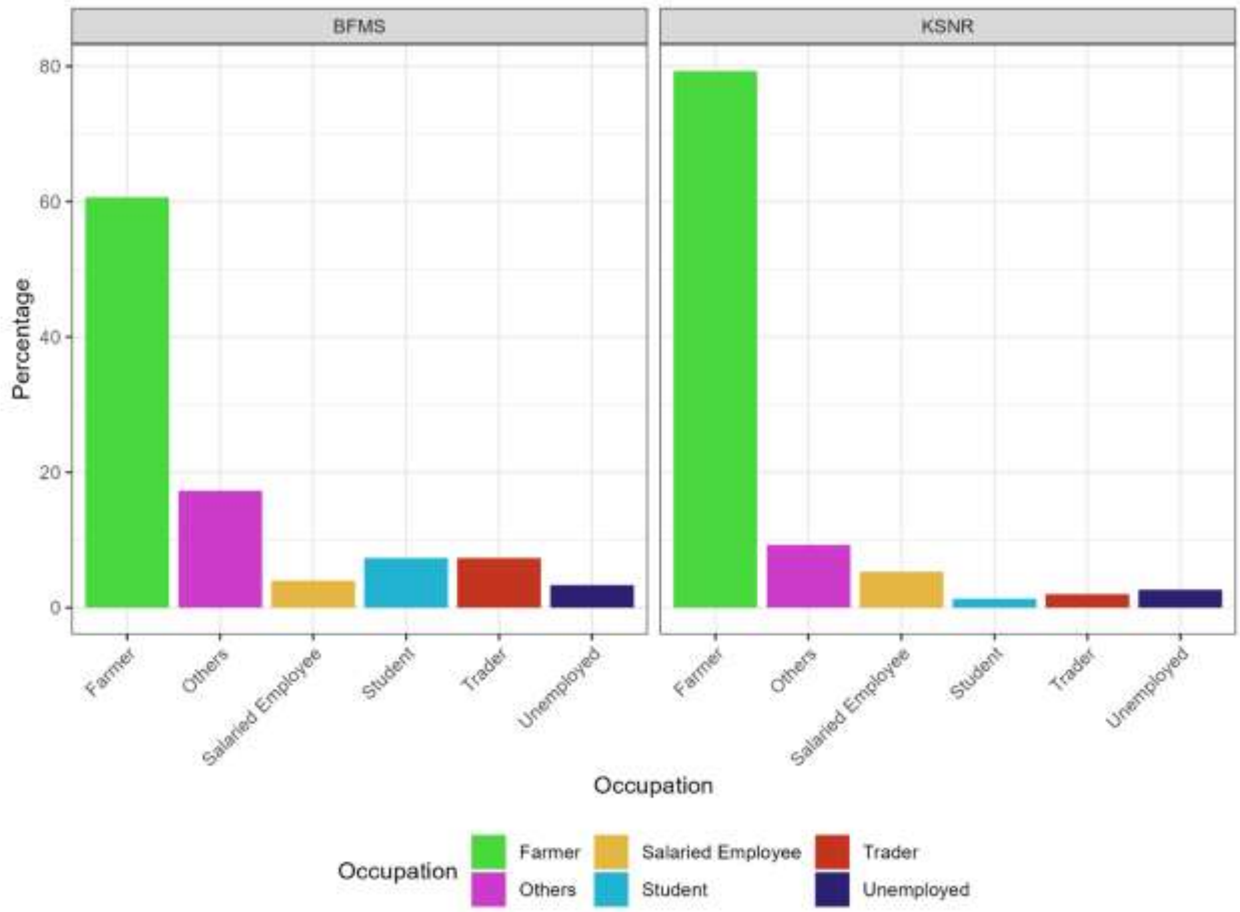

Figure 4.15: Distribution of respondents' occupation in BFMS and KSNR.

Another notable socioeconomic aspect is the distinction between indigenes and settlers in the two sites. The majority of respondents in BFMS identified as indigenes, while most respondents in KSNR were settlers (Figure 4.16). The settlers in KNSR have lived there for more than 20 years, having migrated in search of arable land for farming. This migratory pattern, as noted by Oduro-Ofori et al. (2015) has implications for land tenure, community dynamics and the sustainability of forest resources.

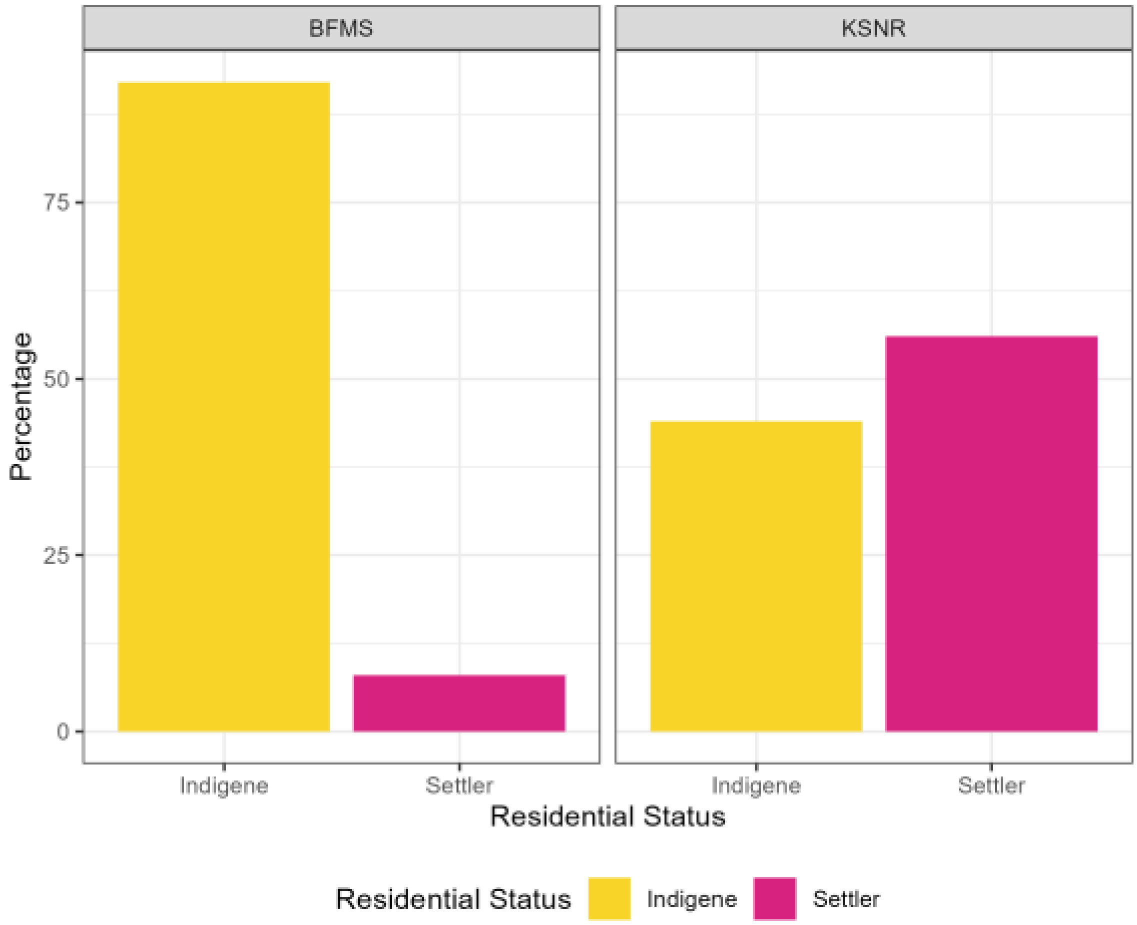

Figure 4.16: Residential status of respondents in BFMS and KSNR.

4.5.2 Forest Conservation Practices from Local Communities' Perspectives

The findings from this research revealed that forest conservation practices, as viewed by local communities near wildlife-protected areas, are important for the sustainability of the forests. In BFMS, 38.6% of respondents indicated that the forest could be conserved if it is protected against wildfires (

Table 4.9). In comparison, 37.2% of respondents in KSNR emphasised the need to employ additional staff for forest protection (

Table 4.9). Although a majority (about 60%) of the respondents did not consider staffing to be a significant issue affecting conservation activities, previous research studies by Oduro-Ofori et al. (2015) and Ayivor & Ntiamoa-Baidu (2015) noted that the retirement of staff without adequate replacements had hindered forest management, highlighting the need for staff capacity enhancement and better equipment. Buildings that were previously occupied by staff remain uninhabited and are deteriorating, an observation noted during fieldwork. However, no official data from the management of the reserve was obtained to support claims about the adequacy of staffing.

Additionally, respondents in KSNR highlighted challenges posed by group hunting in the forest. Many individuals report being threatened or attacked when attempting to prevent unauthorised hunting. Evidence of illegal hunting activities was observed during fieldwork in KSNR. Fires are often started during hunting activities to drive wild fauna such as antelopes and grass cutters from their habitats, facilitating their capture. Unfortunately, these fires frequently spread uncontrollably, causing extensive damage to the vegetation. Janssen et al. (2018) also documented an annual recurrence of fire in KSNR due to anthropogenic activities such as hunting. These practices have detrimental effects on the forest including loss of biodiversity and decline of soil fertility. Afriyie et al. (2021c) corroborated an increase in hunting activities in the nature reserve and recommended the recruitment of additional staff to enhance forest protection.

Another concerning observation was the practice of slash-and-burn agriculture, which is common in both sites. Farmers clear land by setting fires, which, in the dry conditions of the transition zone, can easily spread to adjacent forested areas. Afriyie et al. (2021b) and Amankwah et al. (2021) corroborated that farming practices in the study sites involve this slash-and-burn method of land preparation. Given the dry conditions of the transition zone, these fires easily spread to adjacent forested areas, contributing to forest degradation. According to Tang & Yap (2020), the lack of extended fallow periods in slash-and-burn agriculture leads to soil nutrient depletion and reduced crop yields. While these practices are deeply rooted in the agricultural systems of local communities, targeted education, awareness and intervention can mitigate and potentially put a stop to these harmful practices.

From a policy perspective, more than 15% of respondents (19% in BFMS and 16% in KSNR) called for stronger enforcement of forest-related legislation. This suggests that many community members see the role of law enforcement and policy in protecting the forest, especially in light of illegal hunting, logging and clearing activities. However, effective legislation requires robust mechanisms and community involvement, which is reiterated by 4.6% of respondents from

Kogyae requesting for intensification of management. Moreover, 13.3% of respondents in KSNR and 4.4% in BFMS expressed the desire for greater local involvement in forest conservation efforts. This shows the importance of engaging local communities in the design and implementation of conservation programs, as they are often the best positioned to understand and address unique challenges in their areas as emphasised by Boafo et al. (2016).

Additionally, 7.1% of respondents in BFMS and 11.8% in KSNR called for increased community education on the importance of forests. This finding suggests that while awareness levels may be high in some respects, there remains room for improvement, particularly in communicating the long-term benefits of forest conservation. Educational programs should focus on sustainable farming practices, biodiversity conservation and the role of forests in climate modulation. Such initiatives can foster greater community buy-in and compliance with conservation measures. This aligns with Dehghani Pour et al. (2023), who mentioned the importance of educating and building the capacity of the local population to enhance the benefits of forest management.

Finally, 9.3% of BFMS proposed the planting of indigenous species as a strategy for forest restoration and conservation. Indigenous species are well-adapted to local environmental conditions and provide ecosystem services, including carbon sequestration.

Table 4.9: Forest conservation practices from the perspectives of the local communities.

Conservation practices	BFMS (%)	KSNR (%)
Implementation of wildfire preventive measures	38.6	6.5
Staffing up the forest protection unit	1.8	37.2
Educating the populace about the importance of the forest	7.1	11.8
Enforcement of forest legislation	19	16.3
Prohibiting illegal felling of trees	7.1	
Regulating hunting activities		3.8
Enforcement of penalties for forest law violators	3.5	2.7
Engagement of the community in forest conservation programs	4.4	13.3
Replanting indigenous tree species	9.3	
Intensifying management		4.6
Introduction of an alternative source of livelihood	2.2	
Others	7	3.8

4.5.3 Socio-demographic Influence on Forest Conservation Knowledge

The results of the Multinomial Logistic Regression (MLR) analysis indicated that socio-demographic variables, including education level, age, sex and residential status, did not significantly influence respondents' perspectives on forest conservation practices in either BFMS or KSNR (Table 4.10). This finding contrasts with earlier studies that identified socio-demographic variables as key determinants of conservation knowledge, behaviour, and engagement. This finding contrasts previous studies that have reported socio-demographic variables as significant determinants of conservation knowledge, practices and engagement. For instance, Tamene et al. (2024) and Zoderer et al. (2016) found that cultural background and age were key factors influencing botanical knowledge and conservation practices in Ethiopia and Italy, respectively. Similarly, Ito & Kawazoe (2018) highlighted that education level and household income play significant roles in shaping knowledge of conservation practices.

The lack of significant influence in this study suggests that, within BFMS and KSNR, local communities may already share a baseline level of conservation awareness, minimising the variability introduced by socio-demographic factors. Several contextual factors may explain this pattern. First, long-standing community interactions with the forest may have fostered a collective understanding of conservation practices, independent of formal education or demographic variations. Oduro-Ofori et al. (2015) corroborated that local community knowledge in KSNR had relevance in the management of their forests. Furthermore, traditional ecological knowledge systems and direct involvement in conservation practices, such as community-based forest management initiatives, may play a more pivotal role in shaping forest conservation perspective than individual socio-demographic attributes. Attuquayefio & Gyampoh (2010), similarly observed that indigenous knowledge in BFMS has positively contributed to wildlife conservation efforts in BFMS, reiterating the importance of local engagement. Thus, while prior literature underscores the influence of socio-demographic factors on conservation practices, the findings of this study highlight the need to consider local context cultural dynamics and community-driven environmental governance in understanding how perspectives on forest conservation practices are shaped.

Table 4.10: Multinomial Logistic Regression (MLR) results of socio-demographic variables influencing forest conservation knowledge in BFMS and KSNR.

	BFMS				KSNR			
	Coefficient	Std. err.	t	P>t	Coefficient	Std. err.	t	P>t
Education (not educated)								
Primary school	-0.27	0.26	-1.01	0.31	-0.09	0.21	-0.41	0.68
Junior high/middle school	-0.20	0.22	-0.93	0.35	0.23	0.17	1.34	0.18
Senior high school	0.11	0.31	0.37	0.72	0.22	0.20	1.08	0.28
Tertiary level	0.08	0.30	0.28	0.78	0.49	0.28	1.73	0.09
Age (20-30)								
31-40	0.17	0.22	0.76	0.45	0.16	0.20	0.84	0.40
41-50	0.22	0.27	0.83	0.41	0.15	0.22	0.67	0.50
50 upwards	0.00	0.24	0.01	0.99	-0.24	0.21	-1.14	0.26
Sex (Male)								
Female	0.05	0.15	0.31	0.76	-0.19	0.16	-1.22	0.22
Residential Status (native)								
Settler	-0.25	0.27	-0.92	0.36	-0.09	0.13	-0.69	0.49

CHAPTER 5

CONCLUSIONS, RECOMMENDATIONS AND PERSPECTIVES

5.1 Conclusions

This study assessed the effects of anthropogenic activities on carbon stocks, examined the influence of soil properties on woody species abundance, conservation status and explored conservation practices in Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR). The findings have significant ecological and conservation implications:

- The decline in carbon stocks (-40,236 Mg C in BFMS and -272,109 Mg C in KSNR) highlights the impact of anthropogenic activities such as charcoal production, poaching and agricultural expansion. These losses compromise the carbon sequestration potential of protected areas and their role in mitigating climate change.
- Soil properties accounted for a considerable portion of the variation in woody species abundance (40.27% in BFMS and 34.41% in KSNR), indicating that soil nutrient dynamics significantly influence forest structure and species distribution. Furthermore, bulk density (B.D), base saturation (B.S), sodium (Na), phosphorus (P), pH and total nitrogen (T.N) were key determinants of woody species abundance in the protected areas.
- The conservation values (GHI of 134.24 in BFMS and 105.41 in KSNR) emphasize the ecological importance of these forests, while the negative Red List Index (-1.55 in KSNR) suggests urgent conservation needs due to the presence of threatened woody species.
- Community perspectives on conservation varied between sites, with BFMS respondents prioritizing wildfire prevention and KSNR respondents advocating for increased staffing. Socio-demographic characteristics (sex, age, educational level and residential status) did not significantly influence community perspectives on forest conservation practices. These findings reinforce the necessity of integrated conservation strategies that incorporate community engagement, improved forest governance, and enhanced monitoring systems to sustain the ecological integrity of protected areas.

5.2 Recommendations

To effectively address the challenges identified, the following recommendations are proposed:

5.2.1 For Decision-Makers and Policymakers

- Strengthen in-situ conservation to protect vulnerable, threatened, endangered and species of high conservation concern.
- Develop and implement policies supporting carbon trading initiatives and payment for ecosystem services to incentivise conservation.
- Strengthen forest governance by fostering collaborations between government agencies, conservation organisations and local communities.
- Increase financial support for conservation programs, including staffing, capacity-building, and infrastructure development in protected areas.

5.2.2 For Practitioners and Conservation Organizations

- Implement community-based conservation programs that empower local populations to participate in sustainable forest management.
- Enhance technical training for forest rangers and conservation staff to improve monitoring and enforcement against illegal activities.
- Promote agroforestry and sustainable land-use practices to reduce pressure on protected forests while supporting livelihoods.

5.2.3 For Local Communities and Stakeholders

- Strengthen community outreach and education programs to enhance awareness of conservation benefits and responsibilities.
- Establish and support local conservation committees to facilitate grassroots participation in biodiversity protection.
- Encourage alternative livelihoods such as ecotourism and non-timber forest product utilisation to reduce dependency on destructive forest activities.

5.2.4 Perspectives for Future Research

To build on the findings of this study, future research should focus on:

- Long-term Carbon and Soil Monitoring: Establishing permanent plots for continuous assessment of carbon stock changes and soil nutrient dynamics to better understand long-term ecological trends.
- Climate-Soil-Vegetation Interactions: Investigating how climate variability influences soil properties and, in turn, affects forest resilience and species composition.
- Socioeconomic and Policy Impacts: Analysing how conservation policies, land tenure systems, and community engagement strategies influence biodiversity conservation in protected areas.
- Remote Sensing and Advanced Modeling: Utilising high-resolution satellite imagery, drone technology, and machine learning approaches to improve forest monitoring and conservation planning.
- Genetic Studies: Exploring genetic diversity and adaptive potential of key species for conservation and restoration efforts.

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APPENDICES

Appendix 1: List of publication

1. Amankwah, A.A., Quaye-Ballard, J.A., Kouassi, E.K., Porembski, S., Manu, E.A. and Adu-Bredu, S. (2024). Effect of anthropogenic activities on carbon stocks in protected areas within Ghana's forest-Savannah transition zone. *Trees, Forests and People*, *17*, p.100641. https://doi.org/10.1016/j.tfp.2024.100641

2. Amankwah, A. A., Kouassi, E. K., Porembski, S., Quaye-Ballard, J. A., Zrehon, M. W., Mendy, P. A., Okorie, B. C., Agboka, K.-M. J., Dwumah, K. A., Opuni-Frimpong, N. Y., & Adu-Bredu, S. (2025). Forest conservation practices: Insights of local communities near wildlife-protected areas in Ghana. Journal of Agriculture and Rural Development in the Tropics and Subtropics, 126(2).

Appendix 2: Woody species distribution across the different LULC types in BFMS

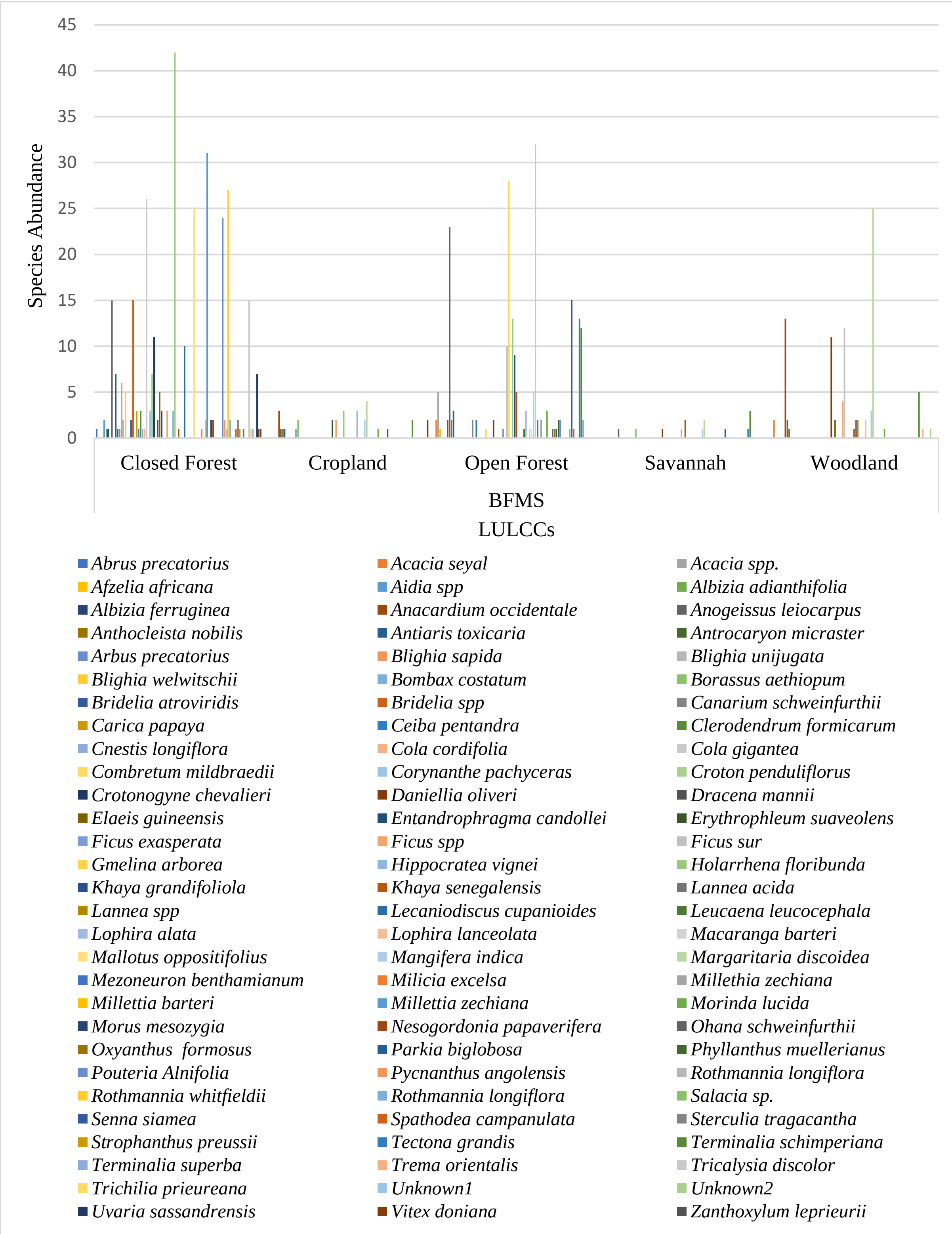

Figure S1: Distribution of woody species within LULC of BFMS.

Appendix 3: Woody species distribution across the different LULC types in KSNR

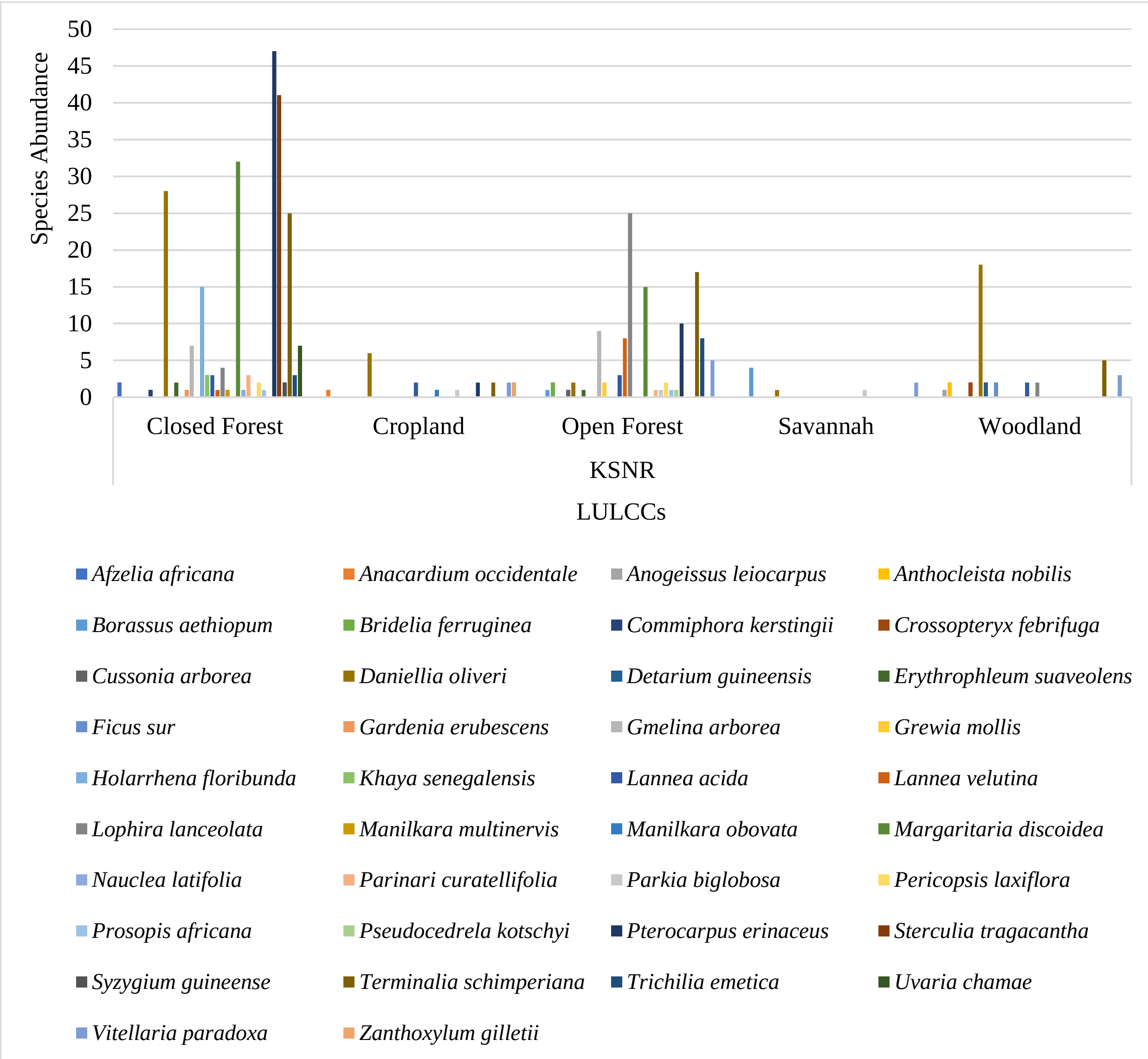

Figure S2: Distribution of woody species within the LULC of KSNR

Appendix 4: Families in BFMS and KSNR.

Table S1: Count of the different families in BFMS and KSNR.

BFMS		**KSNR**	
Family	Count of Species	Family	Count of Species
Anacardiaceae	5	Anacardiaceae	3
Annonaceae	1	Annonaceae	1
Apocynaceae	2	Apocynaceae	1
Arecaceae	2	Araliaceae	1
Asparagaceae	1	Arecaceae	1
Bignoniaceae	1	Burseraceae	1
Burseraceae	2	Chrysobalanaceae	1
Caricaceae	1	Combretaceae	2
Celastraceae	2	Euphorbiaceae	1
Combretaceae	5	Fabaceae	9
Connaraceae	1	Gentianaceae	1
Euphorbiaceae	8	Lamiaceae	2
Fabaceae	19	Malvaceae	2
Gentianaceae	1	Meliaceae	3
Lamiaceae	3	Moraceae	1
Loganiaceae	1	Myrtaceae	1
Malvaceae	6	Ochnaceae	1
Meliaceae	4	Phyllanthaceae	1
Moraceae	6	Rubiaceae	3
Myristicaceae	1	Rutaceae	1
Ochnaceae	2	Sapotaceae	3
Papilionacaeae	1		
Phyllanthaceae	1		
Rubiaceae	8		
Rutaceae	1		
Sapindaceae	6		
Sapotaceae	2		
Ulmaceae	1		
Verbenaceae	1		

Appendix 5: Accuracy Assessment for the Land Use Land Cover Classifications

Table S2: Accuracy assessment for BFMS: 1992

	Reference Total	Classified Total	Number of Correct	Producers Accuracy (%)	User Accuracy (%)	Kappa Statistics
Closed Forests	40	75	35	87.50%	46.67%	0.62
Open Forests	38	36	30	78.95%	83.33%	0.75
Woodlands	30	28	25	83.33%	89.29%	0.81
Savannahs	28	20	18	64.29%	90.00%	0.70
Croplands	32	22	20	62.50%	90.91%	0.68
Built-up/ Bare lands	32	29	22	68.75%	75.86%	0.73
Total	200	200	150	**Overall Classification** 75.00%		**Overall Kappa Statistics** 0.72

Table S3: Accuracy assessment for BFMS: 2010

	Reference Total	Classified Total	Number of Correct	Producers Accuracy (%)	User Accuracy (%)	Kappa Statistics
Closed Forests	35	38	32	**91.43%**	**84.21%**	**0.78**
Open Forests	40	42	37	**92.50%**	**88.10%**	**0.81**
Woodlands	30	28	24	**80.00%**	**85.71%**	**0.79**
Savannahs	28	26	22	**78.57%**	**84.62%**	**0.76**
Croplands	37	36	31	**83.78%**	**86.11%**	**0.80**
Built-up/ Bare lands	30	30	24	**80.00%**	**80.00%**	**0.81**
Total	200	200	170	**Overall Classification** 85.00%		**Overall Kappa Statistics** 0.80

Table S4: Accuracy assessment for BFMS: 2023

	Reference Total	Classified Total	Number of Correct	Producers Accuracy (%)	User Accuracy (%)	Kappa Statistics
Closed Forests	36	38	34	**94.44%**	**89.47%**	**0.80**
Open Forests	42	45	40	**95.24%**	**88.89%**	**0.83**
Woodlands	30	28	26	**86.67%**	**92.86%**	**0.81**
Savannahs	27	25	23	**85.19%**	**92.00%**	**0.80**
Croplands	35	37	32	**91.43%**	**86.49%**	**0.82**
Built-up/ Bare lands	30	27	25	**83.33%**	**92.59%**	**0.81**
Total	200	200	176	**Overall Classification** 88.00%		**Overall Kappa Statistics** 0.82

Table S5: Accuracy assessment for KSNR: 1992

	Reference Total	Classified Total	Number of Correct	Producers Accuracy (%)	User Accuracy (%)	Kappa Statistics
Closed Forests	42	55	34	**80.95%**	**61.82%**	**0.61**
Open Forests	36	42	29	**80.56%**	**69.05%**	**0.70**
Woodlands	30	22	19	**63.33%**	**86.36%**	**0.75**
Savannahs	28	20	15	**53.57%**	**75.00%**	**0.66**
Croplands	32	30	21	**65.63%**	**70.00%**	**0.65**
Built-up/ Bare lands	32	31	28	**87.50%**	**90.32%**	**0.82**
Total	200	200	146	**Overall Classification** 73.00%		**Overall Kappa Statistics** 0.71

Table S6: Accuracy assessment for KSNR: 2010

	Reference Total	Classified Total	Number of Correct	Producers Accuracy (%)	User Accuracy (%)	Kappa Statistics
Closed Forests	45	50	40	**88.89%**	**80.00%**	**0.75**
Open Forests	38	42	35	**92.11%**	**83.33%**	**0.78**
Woodlands	32	28	25	**78.13%**	**89.29%**	**0.80**
Savannahs	30	26	22	**73.33%**	**84.62%**	**0.72**
Croplands	30	32	26	**86.67%**	**81.25%**	**0.76**
Built-up/ Bare lands	25	22	19	**76.00%**	**86.36%**	**0.79**
Total	200	200	164	**Overall Classification** 82.00%		**Overall Kappa Statistics** 0.78

Table S7: Accuracy assessment for KSNR: 2023

	Reference Total	**Classified Total**	**Number of Correct**	**Producers Accuracy (%)**	**User Accuracy (%)**	**Kappa Statistics**
Closed Forests	35	37	32	**91.43%**	**86.49%**	**0.79**
Open Forests	40	43	38	**95.00%**	**88.37%**	**0.82**
Woodlands	28	26	24	**85.71%**	**92.31%**	**0.80**
Savannahs	26	24	22	**84.62%**	**91.67%**	**0.79**
Croplands	34	36	30	**88.24%**	**83.33%**	**0.81**
Built-up/ Bare lands	37	34	28	**75.68%**	**82.35%**	**0.78**
Total	200	200	172	**Overall Classification** 86.00%		**Overall Kappa Statistics** 0.81

Appendix 6: Pictures of Study Area

Figure S3: The Research Team at Boaben-Fiama Monkey Sanctuary (BFMS)-(*Photo by Afua Amponsah Amankwah*).

Figure S4: The Research Team at Kogyae Strict Nature Reserve (KSNR)-(*Photo by Afua Amponsah Amankwah*).

PUBLICATIONS

Trees, Forests and People 17 (2024) 100641

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

Effect of anthropogenic activities on carbon stocks in protected areas within Ghana's forest-Savannah transition zone

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ARTICLE INFO

Keywords:
Climate change mitigation
Carbon pool
Carbon stock
Carbon sequestration
REDD+

ABSTRACT

Tropical forests play a significant role in climate change by sequestering atmospheric carbon dioxide. However, deforestation and forest degradation adversely affect these forests' carbon stocks. Reports indicate that anthropogenic activities have led to forest degradation and deforestation in Boabeng Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR). This study assessed the effects of these activities on the carbon stocks of BFMS and KSNR. Using satellite imagery, field measurements and allometric models, carbon stocks of the study area were assessed from 1992 to 2023. The assessment revealed significant losses attributed to anthropogenic activities, such as hunting, farming and charcoal burning. BFMS experienced a total loss of 40,236 Mg C, while KSNR lost 272,109 Mg C. The closed forests had the highest carbon stock amongst the different vegetation types, with soil representing the most significant carbon pool in the protected areas, revealing the influence of vegetation structure on carbon sequestration and the need for soil conservation. The substantial carbon sequestration potential observed in the different vegetation types of the study area indicates that the Forest-Savannah Transition Zone is a prospective area for climate change mitigation aligning with the Sustainable Development Goals (Goals 13 and 15) and the National Climate Change Policy of Ghana. These findings provide valuable insights for carbon trading and biodiversity conservation, emphasizing the potential of nature-based solutions in addressing global climate challenges.

1. Introduction

Forests are carbon pools, they can sequester and store carbon in them (Adu-Poku et al., 2023). Forests sequester carbon in their soils and biomass, which serve as low-cost mechanism for carbon sequestration (Golub et al., 2022; Nowak et al., 2013). Globally, forest ecosystems hold nearly 80 % of all terrestrial above-ground carbon and 70 % of all soil organic carbon, which makes them imperative for climate change mitigation (Ameray et al., 2021; Wellbrock et al., 2017). The primary cause of climate change and global warming is the anthropogenic rise in greenhouse gases (GHGs) concentrations in the earth's atmosphere. The primary GHGs are carbon dioxide (76 %) and methane (16 %). Therefore, reducing their concentrations in the atmosphere should take precedence in any climate change mitigation programme (Cuesta et al., 2023; Friedlingstein et al., 2006; Shivanna, 2022). In addition, forests help in adaptation to climate change by improving the resilience of rural communities, conserving biodiversity and maintaining cultural heritage (Awé et al., 2021).

Forests cover about one-third of the earth's terrestrial ecosystem and without disturbances, act as carbon sinks (Adu-Poku et al., 2023). This is because they store more carbon than they release and can live for decades. However, forest degradation and deforestation lead to the emission of carbon dioxide (CO_2) and other GHGs such as nitrous oxide (N_2O) and methane (CH4) in the case of forest fires. These emissions contribute

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https://doi.org/10.1016/j.tfp.2024.100641

Available online 3 August 2024

to climate change and global warming, which have detrimental effects on the environment and human population (Chave et al., 2005; Shivanna, 2022). Forest sequesters 30 % of CO_2 from anthropogenic activities (Magnússon et al., 2016). On the other hand, deforestation and forest degradation account for 12–20 % of global anthropogenic GHG emissions (Saatchi et al., 2011). Anthropogenic climate change is an international discourse, adversely affecting ecosystems and their functioning (Yadav et al., 2022).

Among the initiatives to mitigate the effects of climate change is the Reducing Emissions from Deforestation and Forest Degradation, along with the conservation of forest carbon stocks or biodiversity, sustainable management of forests and enhancement of forest carbon stocks (REDD+) project under the United Nations Framework Convention on Climate Change UNFCCC (2011). The REDD+ aims to address climate change by reducing CO_2 emissions through the conservation and sustainable management of forests, a strategy referred to as 'avoided deforestation' (Miles & Dickson, 2010). Furthermore, REDD+ is based on the theory that healthy forests conserve and increase carbon reserves, whereas their over-exploitation leads to CO_2 emission into the atmosphere. The REDD+ finance provides incentives to support climate change mitigation efforts. Developed countries and various sectors offer funding for this initiative, while developing countries receive incentives to reduce forestry emissions. The REDD+ finance connects payments to reduction in greenhouse gas (GHG) emissions and supports developing countries in implementing results-based projects (Morita & Matsumoto, 2023).

Ghana joined the REDD+ in 2008 through the World Bank's Forest Carbon Partnership Facility (FCPF) Readiness Programme and has participated actively. Ghana's REDD+ strategy initially focused on the high forest zones and expanded to include other ecological zones (National REDD+ Secretariat [NRS], 2016). Ghana's REDD+ implementation goals include creating climate-smart production systems that significantly reduce deforestation and forest degradation emissions over the next 20 years, while enhancing carbon stocks and conserving biological diversity by preserving Ghana's forests (NRS, 2016).

Approximately 40 % of Ghana's land area, estimated to be about 9.17 million hectares, is covered by forests (Afele et al., 2022). The nation's forests are divided into three primary ecological zones; savannah, transition zone and high forest (Ghana Forestry Commission, 2017). The transition zone is in the mid-part of the country and depicts the characteristics of the high forest and savannah zones, making it distinct. Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR) are in the forest-savannah transition zone of Ghana (Amankwah et al., 2021; Armani et al., 2018). BFMS is an important example of how traditional beliefs in Ghana have brought about wildlife conservation (Eshun & Tonto, 2014; Kankam & Sicotte, 2013; Kofi Sarfo-Adu et al., 2022). The forest of the sanctuary is a habitat and food source for primates, including the Colobus vellerosus monkey, which is critically endangered on the International Union for Conservation of Nature (IUCN) Red List (Amankwah et al., 2021; Kankam & Sicotte, 2013). KSNR is the only strict national nature reserve in Ghana designated for research purposes and it also serves as a wildlife habitat (Ayivor & Ntiamoa-Baidu, 2015). Despite their importance, BFMS and KSNR have had instances of forest degradation and deforestation due to anthropogenic activities such as hunting, farming, charcoal burning and illegal logging of trees (Amankwah et al., 2021; Janssen et al., 2018; Kankam & Sicotte, 2013; Yahaya et al., 2015).

This study assessed the impact of these activities on the carbon stocks (the quantity of carbon contained in a carbon pool) of the ecotones. Considerable research on carbon stocks in Ghana's forests shows limited data on the total carbon stock (above-ground, belowground, herbs, litter, soil and deadwood) with even less data available for the transition zones (Adu-Poku et al., 2023; Djagbletey et al., 2018). Given the rising interest in using nature-based solutions, such as forests, to mitigate the effects of climate change at no cost to the environment, monitoring changes in vegetation cover and estimating carbon stocks are practical and effective strategies to achieve this goal. This research focused on integrating allometric models, field measurements, Geographic Information System (GIS), Remote Sensing (RS) and statistical software.

2. Materials and methods

2.1. Study area

BFMS and KSNR are located in the transitional zone between the forest belt of southern Ghana and the savannah woodland of the north (Fig. 1). Both sites have dry semi-deciduous vegetation and are protected areas. BFMS, which is located in the Nkoranza North District in the Bono East Region covers an area of 536 hectares (ha) (Amankwah et al., 2021). The region has an average annual rainfall of 800–1200 mm. It also has a bio-modal rainfall pattern and sees modest rains in September through November in addition to its primary rainy season, which runs from March to June. The region's average annual temperature is around 26 °C (Eshun & Tonto, 2014). BFMS is within longitudes 1° 41 ' 10 " West to 1° 42 ' 15" West and latitudes 7° 41' 30" North to 7° 43' 33" North. The elevation of BFMS is between 321 and 396 m above sea level. Communities surrounding the santuary are Akrudwa Panin, Akrudwa Kuma, Bomini, Boaman, Busunya, Domeabra, Kokrompe, Odumase, Senya and Yefra. The sanctuary's forest provides a habitat for two daytime species of primates (Colobus vellerosus and Cercopithecus campbelli lowei) and one nocturnal primate (Galago senegalensis). The Colobus vellerosus primate is listed as critically endangered on the International Union for the Conservation of Nature (IUCN) list (Amankwah et al., 2021; Kankam et al., 2013). The sanctuary doubles as an eco-tourism site and was awarded for its outstanding performance in tourism in 2016, 2015 and 2014 by the Ghana Tourism Authority.

KSNR, on the other hand, lies within 7° 08' N to 7° 21' N, 0° 59' W to 1° 14' W (Afriyie, et al., 2021). It covers an area of 33,000 ha and is located in the Sekyere District of Ashanti Region (Janssen et al., 2018). The reserve is a habitat to different bird species, ungulates and primates like the spot-nosed monkey (Cercopithecus petaurista) (Afriyie et al., 2021). The annual average rainfall of KSNR is between 1200 and 1300 mm, with an average temperature of about 28 °C (Ayivor et al., 2015). The reserve has an average elevation of 180 m above sea level. Communities within the nature reserve are Domeabra, Sankasaase, Njaya and Congo Nkwanta. The reserve is classified as 1a under the IUCN's categorization. It is a protected area solely for scientific research (Janssen et al., 2018).

2.2. Forest cover classification

Landsat satellite images with a spatial resolution of 30 m were obtained for 1992, 2010 and 2023 from the United States Geological Survey (USGS) Centre for Earth Resources Observation and Science (EROS). Classification was done using both unsupervised and supervised classification methods. Accuracy assessment was performed using 200 referenced Global Positioning System (GPS) points obtained from a field survey in the study area. A post-classification method was used for change detection. The classes are closed forest (continuous canopy at least 60 %, preventing sunlight from reaching the forest floor), open forest (discontinuous canopy with coverage between 15 and 59 %), woodland (scattered trees or shrubs with a grass layer), savannah (dominated by a continuous grass layer with few or no trees), cropland (area under cultivation) and built-up/bare lands. This classification approach provides a comprehensive understanding of the forest cover dynamics in the study area over the three-decade period, aiding in assessing changes due to anthropogenic activities.

2.3. Biomass estimation

A nested plot design was employed. Main plots of size 30 × 30 m and subplots of 10 × 10 m were used. Three subplots were formed

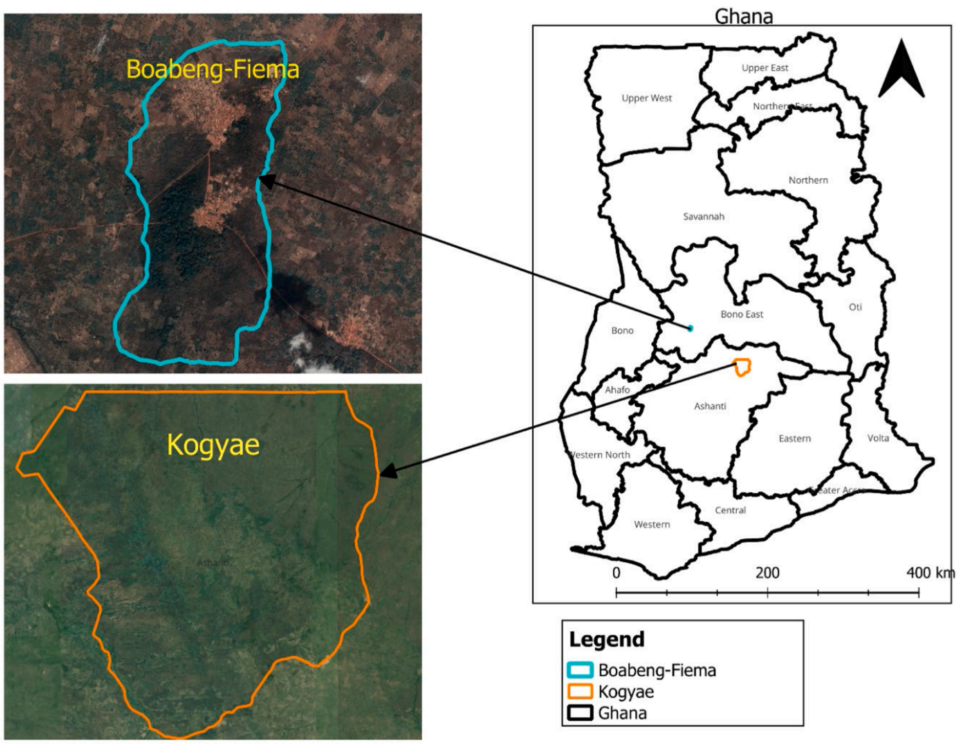

Fig. 1. Study area.

diagonally in each main plot. Five main plots were formed in each vegetation type. One hundred plots (25 main plots and 75 subplots) were created at each site. Tree stem diameter at breast height (dbh) of 1.3 m were measured with diameter tape. The height of the trees was measured using a laser ace hypsometer (TruPulse). In the main plots, trees with a dbh of more than 10 cm were measured, while in the subplots, trees with a dbh of 2.0 to 10 cm were measured. With the assistance of botanists from the Council for Scientific and Industrial Research - Forestry Research Institute of Ghana (CSIR-FORIG), trees were identified based on their species. Voucher specimens were sent to the laboratory for further identification of unidentified species. The species name was used as a surrogate for wood density.

The above-ground mass of the individual trees was estimated based on height, diameter at breast height (dbh), and wood density using the appropriate allometric model. The sum of the individual tree mass was used to calculate the plots' biomass and subsequently carbon stock. The Allometric model (Eq. 1) by Chave et al. (2014) was used for above-ground biomass estimation as:

$$AG = 0.0673\ x\ \left(\rho D^2 H\right)^{0.976}. \tag{1}$$

Where AG = Total aboveground mass (kg); D = diameter at breast height (cm); H = Height (m); and ρ = Wood density (g cm^{-3}). The belowground mas (BG) was calculated by multiplying the AG by 0.25 (Intergovernmental Panel on Climate Change [IPCC], 1996; Handavu et al., 2021), which is the conversion factor.

In the subplots, the non-tree vegetation and forest floor litter (herbaceous plants and litter) were sampled in a 1 × 1 m quadrat. On field, fresh weights were weighed using a digital scale. For dry weight determination, the herbaceous plants and litter samples collected were sent to the laboratory and oven-dried at 60 °C for 72 h to constant weight. Sub-samples were reserved for carbon content analysis.

2.4. Estimation of carbon stocks

2.4.1. Above-ground and belowground carbon

Biomass for each vegetation type was converted to Mega grams of carbon per hectare (Mg C ha-1). The aboveground (AGC) or belowground (BGC) carbon stock of the trees was estimated using Eq. 2 (Adu-Bredu et al., 2021) as;

$$AGC\ orBGC = \sum_{i=1}^{n} (AG \text{ or } BG) \times \frac{10000}{A} \times \frac{CFr}{1000}. \tag{2}$$

where A is area of the plot (m^2), n is the number of trees in the plot and CFr is the carbon fraction for the coversion of the tree biomass to biomass carbon stock. The CFr value used was 0.4748 (Adu-Bredu et al., 2010).

Carbon stock for litter (Lb) and herbs (Hb) (Mg C ha^{-1}) was estimated using Eq. 3 (Adu-Bredu et al., 2021) as:

$$H_b \text{ or } L_b = \frac{1}{n}\sum_{i=1}^{n} \frac{SD_m}{SF_m} \times TF_m \times \frac{10000}{A} \times \frac{CFr}{1000}. \tag{3}$$

where n is number of quadrats, SDm is sample dry mass (g), SFm is sample fresh mass (g), TFm is total fresh mass (kg) and A is area of the quadrat (m^2). Adu-Bredu et al. (2021) found the carbon fraction of the litter and herbs to 0.36, and this was used in the conversion of the herbs and litter to biomass carbon stock.

2.4.2. Soil carbon

Soil samples were taken up to the depth of 15 cm using core samplers. Two sets of samples were taken, with one used for bulk density and the other for soil carbon content analyses. Fresh samples for the bulk density analysis were weighed on the field using a digital scale. The soil samples were taken to the laboratory at CSIR-FORIG for bulk density analysis by oven drying at 105 °C until the weight became constant for dry weight determination. The bulk density was determined by the volume of the core sampler and the oven dry weight of the soil sample. Soil organic carbon (SOC) was determined by the modified dichromate oxidation method of Walkley–Black (Nelson and Sommers, 1982) at the soil laboratory of the CSIR – Soil Research Institute (CSIR-SRI), Kumasi. Soil Carbon Stock (SCS) (Mg C ha^{-1}) was calculated using Eq. (4) as (cf. Adu-Bredu et al., 2021):

$$SCS = BD \times D_P \times SOC \quad (4)$$

Where BD = bulk density, SOC = Soil organic carbon and Dp = soil depth.

2.5. Carbon stock from 1992 - 2023

The AGC estimate for each vegetation type was multiplied by its areal extent calculated from the satellite images to estimate the carbon stock for each vegetation type. The results were summed up to obtain the carbon stock for the years 1990, 2010 and 2023.

2.6. Carbon density

Carbon density, expressed as the Total Carbon Stock (TCS), was calculated by summing the carbon stocks of the different carbon pools. This calculation was performed using Eq. 5 (Pearson et al., 2013; Siraj, 2019).

$$TCS = ACG + BGC + SOC + H_b + L_b \quad (5)$$

2.7. Carbon sequestration potential

Carbon Dioxide Equivalent (CO_2e) serves as a metric to convert the various Greenhouse gas (GHG) estimates into their equivalent amounts in carbon dioxide (CO_2). The molecular weight ratio between carbon dioxide (44) and carbon (12) is 3.67. To determine the carbon sequestration potential of the study area, the TCS was multiplied by this CO_2e (3.67) conversion factor (Ibrahim et al., 2022; Kauffman & Donato, 2012).

3. Results and discussion

3.1. Carbon stock accounting

The forest ecosystem is the largest terrestrial carbon sink, comprising six carbon pools: above-ground, belowground, herbs, litter, soil and deadwood (Martin et al., 2021). This research work considered the following carbon pools: above-ground carbon (AGC), belowground carbon (BGC), soil organic carbon (SOC), herbs and litter. The carbon stock for these different pools was estimated for closed forest (CF), open forest (OF), woodland (WL), savannah (SV) and cropland (CL) within the study area. Soil had the highest carbon stock amongst the various carbon pools in the study area (Fig. 2). This highlights the role of soil in the global carbon cycle and the need for soil conservation. Furthermore, soil is the largest terrestrial carbon pool (Jackson et al., 2017). The study found a significant difference in the AGC and BGC across the vegetation in the study area, suggesting that vegetation types significantly influence carbon storage capacity.

The closed forests had the highest carbon density in the study area (Fig. 3). In BFMS, open forest had the second highest carbon density, followed by savannah, woodland and cropland. Conversely, in KSNR, savannah vegetation had the second highest carbon density, followed by open forest, cropland and woodland. Notably, the savannah vegetation in KSNR had the highest soil carbon stock, augmenting its carbon density.

3.2. Carbon stock estimation from 1992–2023

From 1992 to 2023, the closed forest area in BFMS decreased, whereas the other classes increased (Table 1, Fig. 4). The data for BFMS in 1992 and 2010 were adapted from Amankwah et al. (2021). On the contrary, KSNR experienced an increase in closed forests alongside expansions in both savannah and woodland over the same period (Fig. 5). Open forests in KSNR converted into woodlands. Deforestation leads to

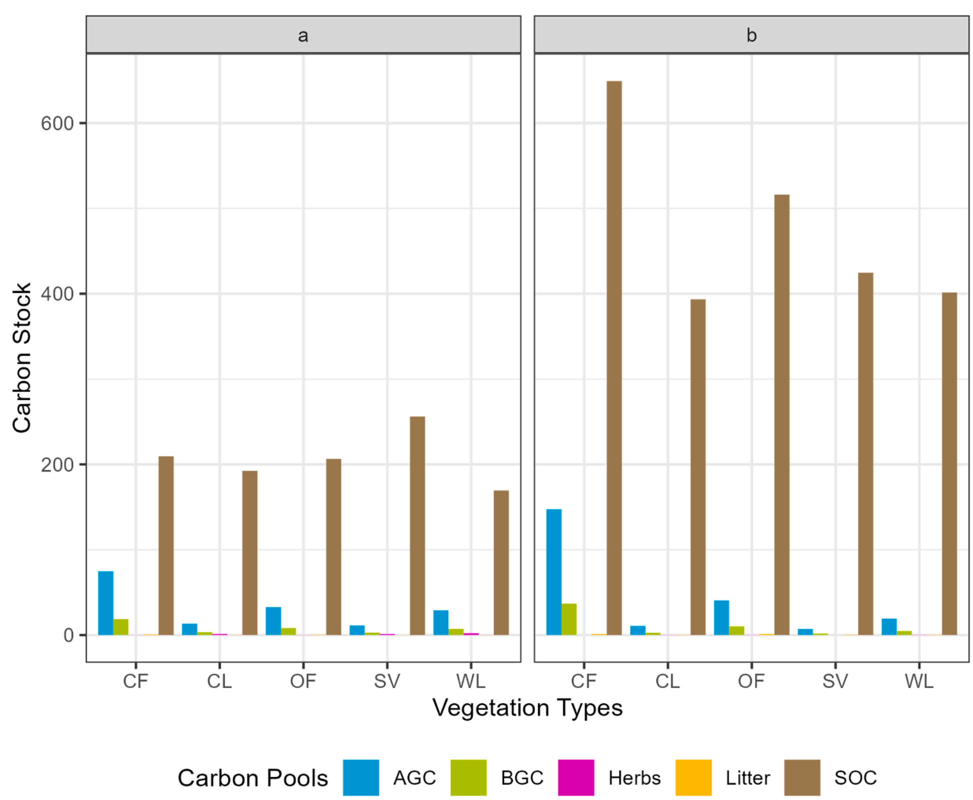

Fig. 2. Carbon stock of the different carbon pools in the various vegetation types in Mg C ha-1; (a) KSNR and (b) BFMS.

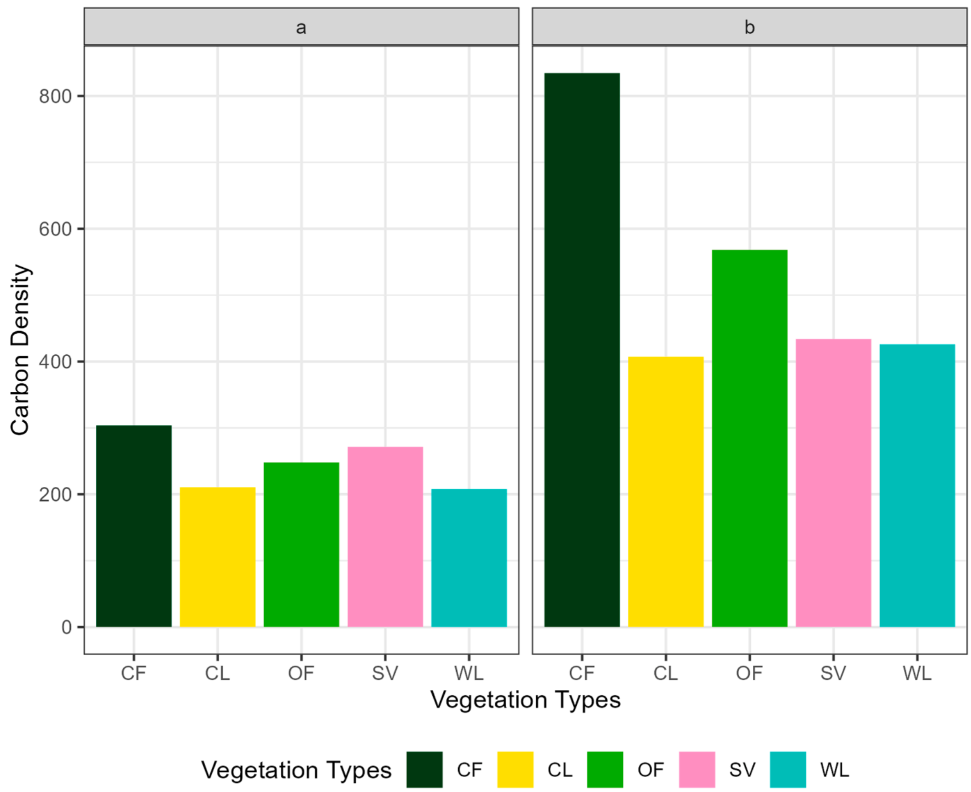

Fig. 3. Carbon density of the different vegetation types in Mg C ha^{-1}; (a) KSNR and (b) BFMS.

Table 1
Spatial extent of the different vegetation/classes in hectares.

Classes	BFMS			KSNR		
	1992	2010	2023	1992	2010	2023
Closed forest	370	205	40	4225	3700	2277
Open forest	31	133	206	10949	5854	8441
Woodland	26	27	81	4879	7732	4439
Savannah	41	33	64	4938	4093	3660
Cropland	28	46	29	4971	3790	3702
Built-up/bare lands	40	92	103	2908	7707	10358

decreased carbon stored in forests and carbon emission into the atmosphere contributing to climate change and global warming (Nogueira et al., 2018).

The carbon stock of the study area decreased from 1992 to 2023. BFMS lost 40,236 Mg C, while KSNR experienced a more substantial loss of 272,109 Mg C (Table 2). This decrease in carbon stock is contrary to Ghana's National Climate Policy (NCCP), which emphasizes increasing carbon sinks and minimising greenhouse gas emissions (MESTI, 2013). Moreover, carbon loss contributes to climate change, global warming and the associated adverse effects (Yoro & Daramola, 2020).

BFMS experienced its highest loss in carbon from 2010–2023 (20,282 Mg C). According to Amankwah et al. (2021), deforestation and forest degradation due to anthropogenic activities such as farming, illegal felling of trees and charcoal production were prevalent from 1992 to 2018, contributing to the sanctuary's declining carbon stock (Table 2). Conversely, KSNR experienced its highest reduction in carbon stock between 1992 and 2010, with a loss of 148,871 Mg C. Janssen et al. (2018) reported a significant decrease in KSNR's forest during this period due to increased human pressure, such as hunting and farming, which caused the deforestation rates to rise from 1.7 % to 5.4 %. The intensified deforestation reflects the substantial carbon loss in the reserve. However, from 2010 to 2023, there was a noticeable reduction in carbon loss in KSNR, which corresponded with the recovery period of the reserve (Janssen et al., 2018).

3.3. Carbon sequestration potential

The use of CO_2e facilitated the assessment of the contribution of the protected areas to climate change mitigation efforts. The amount of carbon sequestered by the different vegetation types (Table 3) indicates their potential for climate change mitigation. Within the framework of REDD+, priority is given to avoiding carbon emissions through conserving forest carbon stocks, sustainable forest management and enhancing forest carbon stocks (Minang & Murphy, 2010). In addition to carbon sequestration, the forests of BFMS serve as a habitat and food source for the primates and an eco-tourism site, thereby promoting cultural heritage and socio-economic prosperity. Furthermore, the forests of both KSNR and BFMS, which are characteristic of transition zones, are rich in tree diversity. Biodiversity acts as a buffer against climate extremes, playing a vital role in climate change by enhancing carbon sequestration, ecosystem services and overall ecosystem functioning (Chen et al., 2023; Hisano et al., 2018; Ray et al., 2023).

A key focus of climate change mitigation and adaptation is employing nature-based solutions. Young forests, when undisturbed, take up more carbon than they emit, while older forests (those over 800 years) may gradually become carbon neutral (Adam et al., 2024; Luyssaert et al., 2008). Nonetheless, these two protected areas can serve as practical solutions for climate change mitigation. Their role in carbon sequestration, biodiversity conservation, and ecosystem services makes them valuable resources for addressing the challenges posed by climate change.

4. Conclusions and way forward recommendations

The considerable carbon sequestration potential of BFMS and KSNR highlights their importance in climate change mitigation and

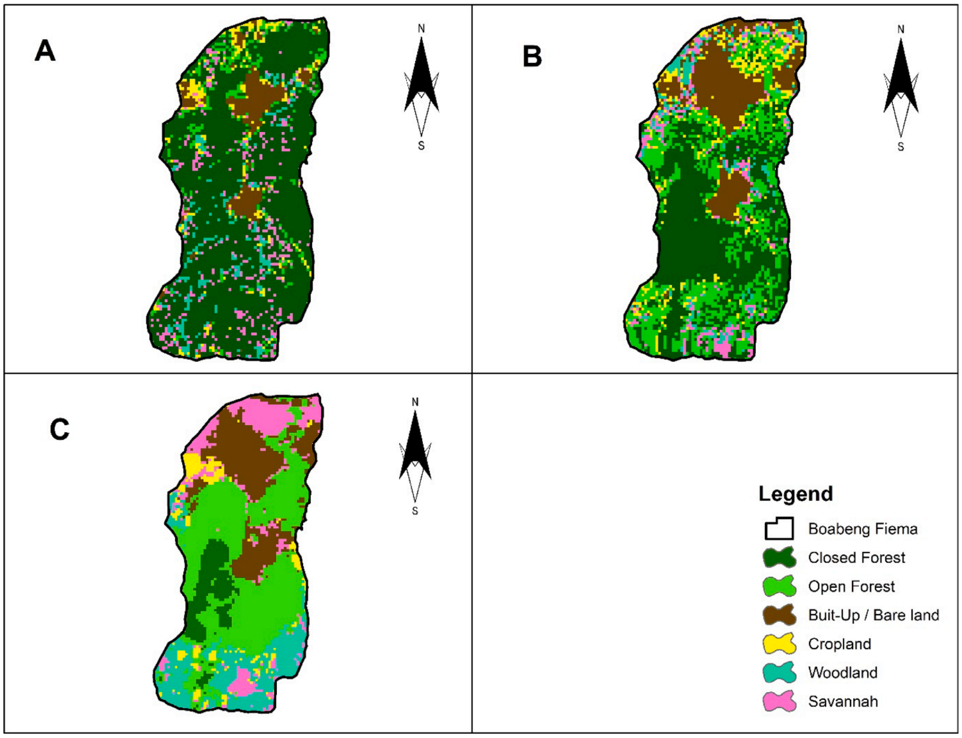

Fig. 4. Classified map of BFMS in three stages: (A)1992, (B) 2010 and (C) 2023.

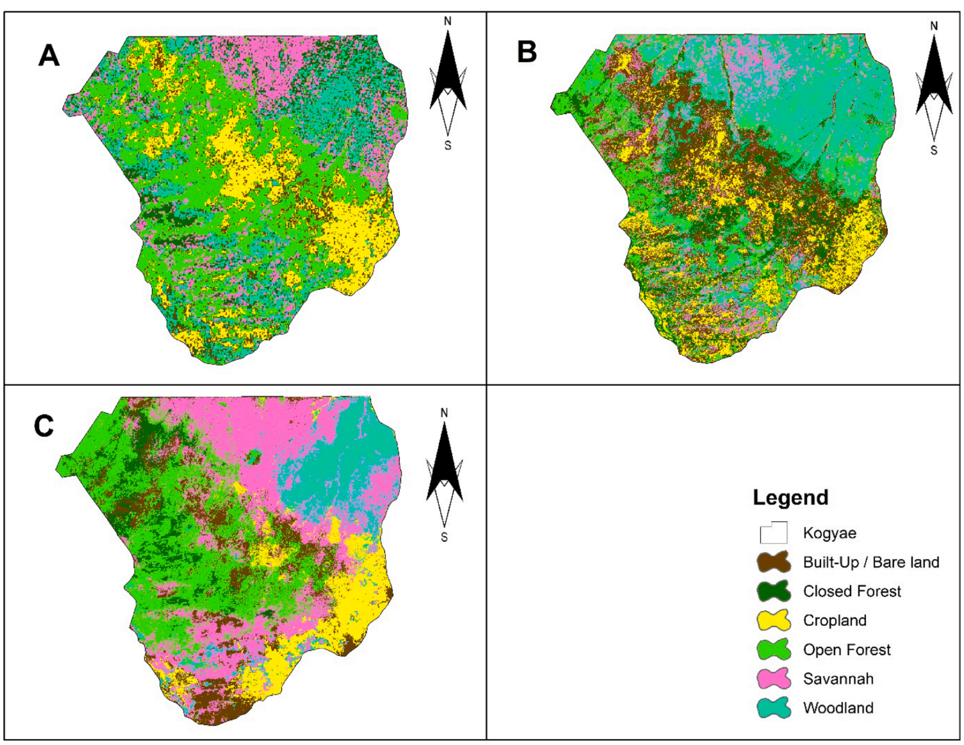

Fig. 5. Classified map of KSNR in three stages: (A)1992, (B) 2010 and (C) 2023.

adaptation. Employing nature-based solutions, such as sustainable management within these protected areas, can effectively reduce carbon emissions, enhance ecosystem resilience and support global climate change mitigation efforts. Addressing and curbing anthropogenic activities within these forests is imperative to preserve their ecological integrity and maximise their carbon sequestration potential. Efforts should focus on implementing strategies to minimize deforestation, forest degradation and unsustainable agricultural practices. The research findings hold significant implications for carbon trading, modelling, international reporting and accountability. The data generated can serve as a valuable foundation for developing carbon offset projects and informing policy decisions related to climate change

Table 2
AGC stock of the study area from 1992 to 2023 in Mg C.

Given year	BFMS	KSNR
1992	56,827	938,865
2010	36,873	789,994
2023	16,592	666,756
Carbon loss 1992–2010	-19,954	-148,871
Carbon loss 2010–2023	-20,282	-123,238
Carbon loss 1992–2023	-40,236	-272,109

Table 3
Carbon sequestration potential of the different vegetation types in Mg C ha-1.

Vegetation type	BFMS		KSNR	
	Carbon density	Carbon sequestration potential	Carbon density	Carbon sequestration potential
CF	835	3,063	304	1,115
OF	568	2,086	248	910
WL	426	1,563	208	764
SV	434	1,593	271	996
CL	407	1,494	211	773

mitigation and biodiversity conservation. Collaborative efforts involving government agencies, conservation organizations, local communities and international stakeholders will be fundamental in implementing and scaling up these recommendations to achieve meaningful and lasting impacts.

Funding

This research was funded by the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) initiative, which is sponsored by the German Federal Ministry of Education and Research (BMBF), as part of doctoral research programme.

CRediT authorship contribution statement

Afua Amponsah Amankwah: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. **Jonathan Arthur Quaye-Ballard:** Conceptualization, Software, Supervision, Validation, Writing – review & editing. **Edouard Konan Kouassi:** Supervision, Writing – review & editing. **Stefan Porembski:** Supervision, Writing – review & editing. **Emmanuel Amponsah Manu:** Data curation, Writing – review & editing. **Stephen Adu-Bredu:** Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known financial or interpersonal conflicts that would have appeared to impact the research presented in this study.

Data availability

Data will be made available on request.

Acknowledgements

We are grateful to the staff and management of the Wildlife Division of Ghana, Forestry Research Institute of Ghana and University of Rostock in Germany and the chiefs, staff and inhabitants of Boabeng-Fiema Monkey Sactuary and Kogyae Strict Nature Reserve.

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Journal of Agriculture and Rural Development in the Tropics and Subtropics
Vol. 126 No. 2 (2025) 57–ff

https://doi.org/10.17170/kobra-2023ghgj7 ISSN: 2363-6033 (online); 1612-9830 (print) – website: www.jarts.info

Forest conservation practices: Insights of local communities near wildlife-protected areas in Ghana

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Abstract

Effective forest conservation relies on active community participation; however, local communities in Ghana are often excluded from policy development. This study explored community perspectives on forest conservation by identifying practices that local inhabitants believed could help preserve the forests in two wildlife-protected areas within the forest-savannah transition zone of Ghana: Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR). A cross-sectional survey involving 300 respondents was conducted using semi-structured questionnaires to gather insights into locally suggested conservation practices. A Multinomial Logistic Regression (MLR) model was employed to assess whether the socio-demographic variables such as age, sex, educational level, occupation and residential status influenced these perspectives. Wildfire prevention was the most emphasised conservation strategy in BFMS (38.6 %), while respondents in KSNR (37.2 %) emphasised increased staffing for effective forest monitoring. Socio-demographic variables had no statistically significant influence ($p > 0.05$) on respondents' perspectives. The findings highlight the importance of integrating local knowledge and community-driven conservation approaches for effective forest management. Strengthening participatory strategies can enhance conservation outcomes and contribute to the achievement of Sustainable Development Goals 13 (Climate Action) and 15 (Life on Land), which focus on biodiversity conservation and ecosystem resilience.

Keywords: biodiversity conservation, forest-savannah transition zone, sustainable forest management

1 Introduction

Communities surrounding protected areas (PAs) hold diverse perspectives on forest conservation practices shaped by interaction with their natural environment (Sobeng *et al.*, 2023). These perspectives influence their engagement in conservation efforts, including selective logging, the establishment of sacred grooves, agroforestry practices and other locally practised forest management techniques (Constant & Taylor, 2020; Kofi Sarfo-Adu *et al.*, 2022). Developed through lived experiences and continuous adaptation to environmental changes, these practices contribute significantly to the sustainable use and protection of forest resources (De-

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hghani Pour *et al.*, 2023). However, despite their key role, local communities are often excluded from formal conservation decision-making, which undermines the effectiveness of sustainable forest management (SFM) and limits the integration of community-driven conservation approaches (Sobeng *et al.*, 2023).

SFM is not only an environmental priority but also a global necessity, particularly in this era of utilising nature-based solutions for climate change mitigation and adaptation. SFM contributes to biodiversity conservation, carbon sequestration, ecosystem stability and sustainable livelihoods. However, deforestation and forest degradation continue to threaten protected areas in Ghana, including Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR), despite their ecological significance (Janssen *et al.*, 2018; Afriyie *et al.*, 2021a; Amankwah *et al.*, 2021). Studies indicate a decline in forest cover and carbon stocks in these areas due to anthropogenic activities. For instance, Janssen *et al.* (2018) reported a doubling of the deforestation rate in KSNR from 1.7 % yr^{-1} to 5.4 % yr^{-1} between 1984 and 2015. Singh *et al.* (2022) documented the near-total clearance of dry forests in KSNR, while Amankwah *et al.* (2021, 2024) reported a 242-hectare decline in BFMS's closed forest between 1992 and 2018 and a loss of 40,236 Mg C in BFMS and 272,109 Mg C in KSNR from 1992 to 2024. These findings highlight the urgent need for improved protection and management strategies in these reserves.

A major barrier to combating deforestation in Ghana has been the exclusion of local communities from policy formulation, planning and implementation of forest management strategies (Adusei & Dunyah, 2016). Research studies conducted in BFMS and KSNR show the limited involvement of local communities in conservation efforts, often due to weak communication, lack of collaboration, and imposed policies that do not integrate community perspectives (Jachmann, 2008; Oduro *et al.*, 2012; Ayivor & Ntiamoa-Baidu, 2015; Oduro-Ofori *et al.*, 2015; Afriyie *et al.*, 2021a; Afriyie *et al.*, 2021b). For instance, Ayivor & Ntiamoa-Baidu (2015) noted that strained communication between management and local communities in KSNR has created conflicts. Oduro-Ofori *et al.* (2015) reported that weak enforcement of resource laws and policy imposition without community participation has increased illegal activities such as agricultural encroachment in KSNR. Furthermore, poor community relations, inadequate staff, and insufficient research and resource inventories in the protected areas (Afriyie *et al.*, 2021a; Afriyie *et al.*, 2021b), have influenced the degree of these pressures. Ghana's 2012 Wildlife and Forest Policy advocates for collaborative forest management, recognising the role of local communities in conservation and the potential socio-economic and ecological benefits of inclusive governance (Ministry of Lands and Natural Resources, 2012). While previous studies have recommended collaborative approaches in PAs (Adusei & Dunyah, 2016; Husseini *et al.*, 2020; Sobeng *et al.*, 2023) few have assessed the forest conservation practices from the perspectives of local communities in BFMS and KSNR.

This study sought to bridge the gap by assessing the forest conservation practices from the perspective of the local communities in KSNR and BFMS and investigating how socio-demographic factors influence community knowledge of forest conservation using a semi-structured questionnaire. By providing empirical evidence on local conservation efforts, the study contributes to policy recommendations for participatory forest management, thereby promoting sustainable forest management and contributing to Sustainable Development Goals (SDGs) 2 (Zero Hunger), 11 (Sustainable Cities and Communities), 13 (Climate Action), and 15 (Life on Land).

2 Method and materials

2.1 Study area

BFMS and KSNR are Wildlife Protected Areas (WPA) located in the forest-savannah transition zone of Ghana. These areas have dry semi-deciduous vegetation serving as important wildlife habitats and are under the management of the Wildlife Division of the Ghana Forestry Commission (Fig. 1). BFMS covers an area of 535 ha and is situated in longitudes 1°41'10" to 1°42'15" W and latitudes 7°41'30" to 7°43'33" N, in the Kintampo Forest District of the Bono East Region (Amankwah *et al.*, 2021). The sanctuary experiences an annual rainfall of 800-1200 mm on average and has a mean annual temperature of 26 °C (Eshun & Tonto, 2014). The elevation of BFMS is approximately 360 m a.s.l. In addition to being an important protected area, BFMS is a national ecotourism site and provides a home to the critically endangered Colobus vellorosus monkey, which is endemic to West Africa and listed on the International Union for Conservation of Nature (IUCN) Red List.

KSNR on the other hand is located in the Sekyere Mampong Forest District of the Ashanti region and spans an area of 33,000 ha. Its coordinates are 7°08' to 7°21' N and 0°59' to 1°14' W, with an annual range from 1200 to 1300 mm. The reserve has an annual temperature of 25 °C (Janssen *et al.*, 2018; Ibrahim *et al.*, 2020; Afriyie *et al.*, 2021b). Surrounding communities include Domeabra, Sankasase, Njaya and Congo Nkwanta. The elevation of KSNR is relatively flat with an average altitude of 180 m a.s.l. The nature reserve is classified as an IUCN 1a strict nature reserve, meaning that visits are permitted solely for research purposes. Human access and use are strictly monitored to preserve and protect the ecological, geological and geomorphological features of the reserve (Ayivor & Ntiamoa-Baidu, 2015).

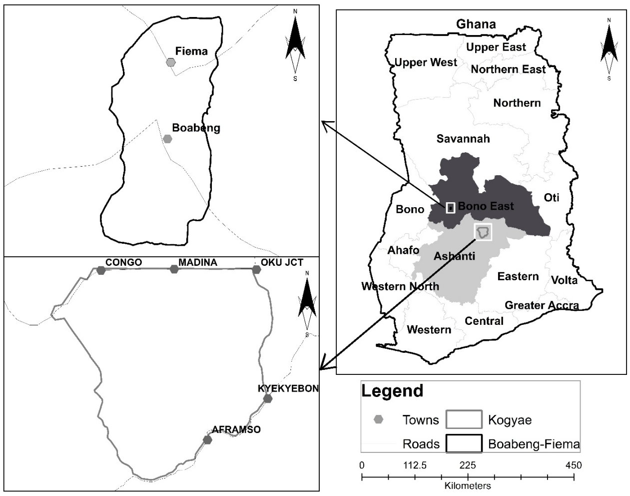

Fig. 1: *Map of the study area showing Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR), both wildlife-protected areas (WPAs) located in the forest-savannah transition zone of Ghana.*

2.2 Sampling technique and sample size

The Nkoranza North District, where BFMS is located, has a population of 56,468, while the Sekyere Central District, encompassing KSNR, has a population of 73,228 (Ghana Statistical Service, 2021). However, the target population for this study was not the entire district population, but rather the adult residents of the selected communities. Based on a reconnaissance survey and consultations with local leaders, including community elders and assembly members, the total adult population was estimated at approximately 1,600 individuals. To determine the appropriate sample size, Slovin's formula was employed. The minimum sample size required for accuracy in estimating proportions was computed by allowing a 5 % margin of error. Thus, the minimum sample size was computed to be 320 respondents. However, due to incomplete responses, data from 300 respondents were analysed.

The distribution of respondents was as follows; Boabeng (n=78), Fiema (n=72) in BFMS, and Congo Nkwata (n=40), Domeabra (n=49), Njaya (n=41) and Sankasaase (n=20) in KSNR. The selected communities were chosen based on their proximity to the reserves. The variation in sample distribution across communities was influenced by differences in population size, household availability and willingness of respondents to participate in the survey. Communities with larger populations had higher representation, while those with smaller populations contributed fewer respondents.

2.3 Data collection

Primary data was collected through (i) questionnaires administered through interviews and (ii) field observations. A semi-structured questionnaire tailored to the local context, comprising both open and closed-ended questions, was developed to gather data on respondents' socio-demographic characteristics and conservation practices related to forest conservation. Prior to the main survey, a pilot study was conducted with a small group to assess the questionnaires' applicability and address any potential misunderstandings. Research assistants from the Forestry Research Institute of Ghana (FORIG) were trained to assist in data collection. Questionnaires were administered through interviews conducted in the local dialect, Twi, with questions translated from English to accommodate respondents' educational and linguistic backgrounds.

The Wildlife Division of Ghana, under the Forestry Commission and the local authorities including chiefs and assembly committee, approved this study. The research team followed community entry procedures, including a formal introduction at the chiefs' palaces and consultation with assembly committee leaders. Announcements about the research activities were disseminated through local information centres within the towns. This collaborative approach ensured transparency, respect for local authority and community engagement.

Respondents were fully briefed on the research's purpose, scope and confidentiality measures before the interviews. They were informed that participation was voluntary, and they could withdraw at any point. To ensure a representative sample of the population, surveys were conducted at households, workplaces and town centres. Data collection schedules were adjusted to accommodate the community's farming activities with interviews conducted during late afternoons and weekends.

A systematic random sampling method was employed, with the local communities divided into clusters based on specific locations; Boabeng and Fiema in BFMS and Domeabra, Sankasase, Nyaja and Congo Nkwanta in KSNR. Starting points within each community were randomly selected and households were surveyed along predetermined routes using a fixed sampling interval of every third household (i.e., after sampling one household, the next household was skipped and the subsequent one was surveyed). The transects were spaced approximately 50 metres apart to ensure adequate coverage of the community. For this study, a respondent is defined as an individual aged 18 years or older who resides in the selected communities and voluntarily agreed to participate in the survey. Respondents were selected randomly from the eligible population within each of the selected communities. It is important to note that no specific predefined protocols or selection criteria were applied to target respondents based on their knowledge or experience related to local forests or conservation practices. The study aimed to capture a broad spectrum of perspectives from community members, allowing for a general understanding of the communities' views on forest conservation practices.

2.4 Data analysis

The data collected from the questionnaires were cleaned, coded and analysed using Statistical Package for Social Sciences (SPSS). The software facilitated data management and computation of descriptive statistics to summarise the socio-demographic variables of respondents. Demographic variables such as sex, age, educational level, occupation and residential status were summarised in a table.

Respondents' perspectives on forest conservation practices were captured through an open-ended question: "What practices do you think can help preserve the forest in your area?" The responses were grouped into thematic categories – such as wildfire prevention, staffing of forest protection units, community engagement, reforestation, alternative livelihoods and enforcement of forest laws – based on a qualitative coding framework developed during data review. Each conservation theme was then converted into a categorical variable with multiple outcomes (e.g., 1 = wildfire prevention, 2 = staffing of forest protection units, 3 = community engagement, etc), which were used as the dependent variables for analysis.

Since respondents could mention multiple conservation practices, each theme was treated as a separate outcome. Multinomial logistic regression (MLR) was conducted for each conservation practice to assess whether socio-demographic variables influenced the likelihood of a respondent mentioning each specific conservation practice.

The general form of the MLR model used is:

$$\log\left(\frac{P(Y_i = k)}{P(Y_i = 0)}\right) = \beta_0^k + \beta_1^k \text{Age}_i + \beta_2^k \text{Sex}_i + \beta_3^k \text{Education}_i + \beta_4^k \text{Residential Status}_i + \varepsilon_k$$

Where: Y_i is the categorical variable indicating the specific conservation practice mentioned by respondent i.
$P(Y_i = k)$ is the probability that respondent i. mentioned conservation practice k.
$P(Y_i = 0)$ is the reference category, representing respondents who did not mention any practice.
β_0^k is the intercept for category k.
$\beta_1^k, \ldots, \beta_4^k$ are the coefficients for the socio-demographic predictors (age, sex, education and residential status) for conservation practice k. ε_k is the error term for each.

Separate models were estimated for each conservation theme (e.g., wildfire prevention, staffing, education). Statistical significance was assessed at a 95 % confidence level ($p < 0.05$) and results were interpreted accordingly to identify demographic predictors of conservation practices.

3 Results

The socio-demographic profiles of respondents (Table 1) indicate that both BFMS and KSNR are characterised by predominantly older, male populations. Notably, BFMS has a higher proportion of formally educated individuals and indigenes, whereas KSNR features a larger share of settlers and a greater reliance on farming.

Table 1: *Socio-demographic characteristics of respondents from Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR).*

Characteristics	*BFMS (%)*	*KSNR (%)*
Sex		
Male	64	72
Female	36	28
Age		
20–30	27	26
31–40	19	23
41–50	17	19
50 upwards	36	31
Educational level		
Not educated	17	35
Primary school	15	11
Junior high/middle school	47	27
Senior high school	10	20
Tertiary level	11	7
Occupation		
Farmer	61	79
Trader	7	2
Salaried employee	4	5
Student	7	1
Unemployed	3	3
Others	17	9
Residential status		
Indigene	92	44
Settler	8	56

Table 2: *Perspectives of forest conservation practices from the local communities near the Boabeng-Fiema Monkey Sanctuary (BFMS) and the Kogyae Strict Nature Reserve (KSNR).*

Conservation practices	*BFMS (%)*	*KSNR (%)*
Implementation of wildfire preventive measures	38.6	6.5
Staffing up the forest protection unit	1.8	37.2
Educating the populace about the importance of the forest	7.1	11.8
Enforcement of forest legislation	19	16.3
Prohibiting illegal felling of trees	7.1	
Regulating hunting activities		3.8
Enforcement of penalties for forest law violators	3.5	2.7
Engagement of the community in forest conservation programmes	4.4	13.3
Replanting indigenous tree species	9.3	
Intensifying management		4.6
Introduction of an alternative source of livelihood	2.2	
Others	7	3.8

Community perspectives on forest conservation (Table 2) differ between the sites. BFMS favours proactive and ecologically restorative measures, such as wildfire prevention and replanting native species, while KSNR emphasises institutional actions, including enhanced forest protection units and improved public education. Additionally, the multinomial logistic regression analysis (Table 3) reveals that none of the examined socio-demographic variables (education, age, sex, residential status) serve as statistically significant predictors of forest conservation knowledge.

4 Discussion

4.1 Socio-demographic characteristics of respondents

The study found a gender imbalance among respondents, with more males than females in both communities, reflecting broader socio-cultural factors. Traditional gender roles, particularly household responsibilities, often limit women's engagement in public and economic affairs in rural Ghana, potentially affecting their participation in forest conservation and decision-making (Bermúdez Figueroa *et al*, 2023). The age distribution showed a predominance of individuals above 50 years, with a notable presence of respondents aged 20-30. This pattern aligns with cultural norms where older individuals, often household heads, are more likely to engage in interviews (Randall & Coast, 2016). However, the study did not assess younger adults explicitly, limiting conclusions about the overall age composition of the community.

Educational levels varied between the study sites, with KSNR having a higher proportion of uneducated respondents compared to BFMS. Most respondents in both areas attained Junior High School education, with the lower educational levels in KSNR corroborating previous findings on educational challenges in the region (Oduro-Ofori *et al*, 2015).

Farming was the dominant occupation, illustrating a strong dependence on forest resources. This aligns with the forest-savannah transition zone's role as an agricultural hub in sub-Saharan Africa (Staver *et al*, 2011). Farming was previously identified as the primary occupation in KSNR (Ayivor *et al*, 2020), reinforcing its central role in local livelihoods. Crop cultivation varied between sites, with maize, yam, rice, and cassava in BFMS, while yam and groundnut dominated KSNR. Agricultural practices, particularly slash-and-burn methods, contribute to deforestation and degradation. Livestock rearing and palm wine tapping were also observed.

A key socioeconomic distinction was the indigenous-settler divide between the sites. Most respondents in BFMS were indigenes, whereas KSNR was largely composed of settlers who migrated over two decades ago in search of arable land. This pattern, as noted by Oduro-Ofori *et al* (2015), has implications for land tenure, community dynamics, and forest resource sustainability.

4.2 Forest conservation practices from local communities' perspective

The study highlights the significance of forest conservation practices as perceived by local communities near wildlife-protected areas. In BFMS, wildfire prevention was a top priority, whereas in KSNR, respondents stressed the need for more personnel to enhance forest protection (Awotwi *et al*, 2018; Amankwah *et al*, 2021). Staffing shortages in KSNR, with deteriorating former staff quarters and no replacements after retirements, mirror longstanding concerns (Ayivor & Ntiamoa-Baidu, 2015; Oduro-Ofori *et al*, 2015). However, official reserve management data on staffing adequacy was unavailable.

KSNR respondents reported threats from external hunters, signifying weakened local enforcement and the need for community-driven monitoring systems. Fieldwork confirmed evidence of illegal hunting, with fires set to drive wildlife out, often leading to uncontrolled forest fires (Afriyie *et al*, 2021a; Janssen *et al*, 2018). These anthropogenic activities accelerate biodiversity loss and soil fertil-

Table 3: *Multinomial Logistic Regression (MLR) results of socio-demographic variables influencing forest conservation perspectives near the Boabeng-Fiema Monkey Sanctuary (BFMS) and the Kogyae Strict Nature Reserve (KSNR).*

	BFMS				*KSNR*			
	Coefficient	*Std. err.*	*t*	*P>t*	*Coefficient*	*Std. err.*	*t*	*P>t*
Education (not educated)								
Primary school	−0.27	0.26	−1.01	0.31	−0.09	0.21	−0.41	0.68
Junior high/middle school	−0.20	0.22	−0.93	0.35	0.23	0.17	1.34	0.18
Senior high school	0.11	0.31	0.37	0.72	0.22	0.20	1.08	0.28
Tertiary level	0.08	0.30	0.28	0.78	0.49	0.28	1.73	0.09
Age (20–30)								
31–40	0.17	0.22	0.76	0.45	0.16	0.20	0.84	0.40
41–50	0.22	0.27	0.83	0.41	0.15	0.22	0.67	0.50
50 upwards	0.00	0.24	0.01	0.99	−0.24	0.21	−1.14	0.26
Sex (Male)								
Female	0.05	0.15	0.31	0.76	−0.19	0.16	−1.22	0.22
Residential Status (native)								
Settler	−0.25	0.27	−0.92	0.36	−0.09	0.13	−0.69	0.49

ity decline. While there are regulations prohibiting poaching and charcoal production (Janssen *et al*, 2018), respondents in KSNR voiced concerns about damage from unsupervised cattle grazing.

Slash-and-burn agriculture was prevalent in both sites, exacerbated by population growth, shorter fallow periods, and climate stress (Daniel Tang & Yap, 2020; Afriyie *et al*, 2021b; Amankwah *et al*, 2021). While rooted in traditional farming, its increasing unsustainability demands intervention that integrates local knowledge and adaptability.

The community's recognition of weak law enforcement presents an opportunity for policy action. While legal frameworks exist, effective regulation requires participatory enforcement. Community members emphasised their role in addressing illegal activities and expressed the need for stronger forest management (Boafo, 2013). Additionally, education was identified as a crucial conservation tool, suggesting room for improvement in fostering long-term forest protection awareness (Dehghani Pour *et al*, 2023).

Finally, 9.3 % of BFMS respondents advocated for restoring degraded forests using indigenous species, citing their ecological benefits (Djagbletey *et al*, 2021). Incorporating community perspectives into reforestation efforts can improve both ecological outcomes and local engagement.

4.3 *Socio-demographic influence on forest conservation knowledge*

The Multinomial Logistic Regression (MLR) analysis revealed that socio-demographic factors – education level, age, sex, and residential status – did not significantly affect respondents' perspectives on forest conservation in BFMS or KSNR. This contrasts studies in Central Alps (Zoderer *et al*., 2016) and South-Central Ethiopia (Tamene *et al*., 2024) where these variables influenced conservation knowledge and engagement.

The absence of a significant effect suggests a shared baseline conservation awareness among these communities, likely shaped by traditional ecological knowledge passed down through generations (Sinthumule & Mashau, 2020; Cebrián-Piqueras *et al*, 2020). Oduro-Ofori *et al* (2015) emphasised the role of local knowledge in forest conservation in KSNR, while Attuquayefio & Gyampoh (2010) documented indigenous knowledge's positive impact on wildlife conservation in BFMS. Direct reliance on forest resources and participation in conservation efforts foster a communal stewardship mindset, potentially outweighing individual socio-demographic influences. This study underscores the importance of cultural context and community-driven governance in shaping conservation perspectives.

4.4 *Implications of the findings on biodiversity conservation*

The lack of correlation between education level and conservation practices in BFMS and KSNR suggests that formal education is not the primary driver of conservation knowledge in these communities. Zoderer *et al*. (2016) and Tamene *et al*. (2024) reported a positive link between education and biodiversity conservation for Central Alps and South-Central Ethiopia, respectively, but this research highlights the importance of traditional ecological knowledge and cultural ties to forests (Oduro-Ofori *et al*, 2015).

These findings suggest that conservation efforts should integrate local knowledge systems rather than rely solely on formal education (Dehghani Pour *et al*, 2023). A key area of application is mitigating slash-and-burn farming, which contributes to deforestation and soil degradation (Tang & Yap, 2020). Conservation strategies should promote sustainable agricultural techniques, such as agroforestry or no-burn methods, that align with both environmental goals and local farming traditions. By bridging indigenous knowledge with modern conservation strategies, biodiversity conservation initiatives can become more effective and culturally attuned.

5 Conclusion

This study underscores the importance of integrating local perspectives with scientific research to enhance forest conservation in BFMS and KSNR. While socio-demographic factors did not significantly influence conservation views, the findings highlight the need for inclusive strategies that engage all community members. Strengthening forest management through increased staffing, law enforcement, and participatory conservation initiatives is crucial for sustainability. Future research should explore community participation in decision-making and conservation actions. By aligning local knowledge with effective policies, BFMS and KSNR can achieve more sustainable forest management outcomes.

Conflict of interest

The authors declare that they have no known financial or interpersonal conflicts that would have appeared to have an impact on the research presented in this study.

Acknowledgements

We extend our appreciation to the Forestry Commission of Ghana, Wildlife Division, chiefs, assembly members, managers, staff, respondents and inhabitants of Boabeng Fiema Monkey Sanctuary and Kogyae Strict Nature Reserve; and Clement Oteng for his support.

Funding

The West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) programme sponsored by the German Federal Ministry of Education and Research (BMBF), funded this research as part of the doctoral research programme.

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