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Conservation status of key protected areas in the forest-savannah transition zone of Ghana based on red list and genetic heat indices

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Abstract

Protected areas are the mainstay of biodiversity, serving as important habitats for endangered and threatened species. However, increasing anthropogenic activities threaten their long-term sustainability. This study assessed the conservation status of Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR), two wildlife-protected areas in the transition zone of Ghana, currently facing human-induced disturbances. The Genetic Heat Index (GHI) and Red List Index (RLI) were used to evaluate the conservation status of the sites. The assessment revealed significant conservation values for BFMS and KSNR, with GHI values of 134.24 and 105.41, respectively. BFMS recorded an RLI value of 0.21, while KSNR had a negative RLI value of − 1.55, primarily due to the prevalence of *Pterocarpus erinaceus*, an endangered tree species on the IUCN Red List. These results reiterate that protected areas are biodiversity hotspots and resilient ecosystems. Immediate action is needed to protect biodiversity and prevent further extinction of valuable tree species. Preserving BFMS and KSNR not only defends against biodiversity loss but also contributes meaningfully to the achievement of Sustainable Development Goals 11 (Sustainable Cities and Communities), 13 (Climate Action) and 15 (Life On Land), particularly in the face of global climate change.

Keywords Biodiversity, Bioquality, Endangered species, IUCN, Monkey sanctuary, Strict nature reserve

1 Background

Protected areas (PAs) are key components in biodiversity conservation. They safeguard natural and cultural resources, support local livelihoods, sustain ecological processes across landscapes and promote sustainable development (Amankwah et al. 2024). In addition to biodiversity conservation, these areas support local livelihoods and wellbeing. Globally, approximately 1.1 billion people rely on protected areas for their livelihoods (Fuente et al. 2020). Protected areas within the transition zone maintain ecological balance and support biodiversity across ecotones (Oliveras and Malhi 2016).

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The forest-savannah transition zone spans throughout the tropics. In Africa, it is primarily found in West African countries, such as Ghana, Côte d'Ivoire, Togo, Benin and Nigeria (Oliveras and Malhi 2016). In Ghana, this zone occupies the middle part of the country (Ametsitsi et al. 2020). Notable protected areas within this transition zone include Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR) (Amankwah et al. 2021; Armani et al. 2018). KSNR is the only designated strict nature reserve in Ghana under the International Union for Conservation of Nature (IUCN) classification. Both sites are composed of species of high conservation concern that require protection (Djagbletey et al. 2021). However, they face increasing anthropogenic pressures, such as bushfires, farming, charcoal burning and hunting, that contribute to forest degradation, biodiversity loss and a decline in carbon stocks (Afriyie et al. 2021; Amankwah et al. 2024).

Despite their ecological importance, the conservation status of these protected areas remains inadequately documented. Addressing this knowledge gap requires robust, science-based indices capable of quantifying biodiversity risk and conservation value. This study adopts two widely recognized tools: the Genetic Heat Index (GHI) and the Red List Index (RLI) to assess the ecological condition and conservation status of BFMS and KSNR.

The Genetic Heat Index (GHI), developed by Hawthorne and Abu-Juam (1995) and revised by Hawthorne and Gyakari (2006), Hawthorne and Gyakari (2006), is a bio-quality assessment tool that measures the conservation value of forests based on species rarity, endemism and ecological distinctiveness. It applies a weighted star rating system to plant species, assigning higher values to globally rare or ecologically significant taxa. This methodology enables the quantification of a site's conservation priority and facilitates comparative assessments across forests. Its strength lies in its simplicity, adaptability, and ability to highlight sites of high conservation concern, as evidenced in studies across Ghana (Djagbletey et al. 2021; Owusu-Prempeh et al. 2018), Cameroon (Tchouto et al. 2006) and other tropical regions (Marshall et al. 2016). However, GHI is not without limitations. It depends heavily on accurate species identification and up-to-date star rating systems (Djagbletey et al. 2021). Additionally, it is primarily floristic and may overlook faunal species of concern. Despite these constraints, recent studies have continued to validate its relevance in conservation planning, especially in understudied ecosystems such as forest-savannah ecotones (Marshall et al. 2016).

The Red List Index (RLI), developed by Butchart et al. (2007), complements the GHI by offering an evaluation of species extinction risk. It aggregates trends in IUCN Red List categories across species groups to produce a single index score. An RLI value close to 1 reflects a stable system with most species considered of least concern, while values near 0 suggest high extinction risk and ecological decline. Its applications have spanned across continents, including tropical forest assessments in Ghana (Owusu et al. 2022), China (Chen et al. 2020) and Peru (Ames-Martínez et al. 2021). RLI's strength lies in its quantitative nature and alignment with IUCN global standards. However, it relies on periodic updates to the Red List, and without these updates, its ability to reflect recent changes or emerging conservation concerns may be limited (IUCN 2025).

Despite these caveats, the complementary nature of GHI and RLI provides a robust framework for assessing ecological resilience and conservation priorities. When used together, they offer a holistic view of conservation status—GHI capturing floristic rarity

and local bioquality, and RLI providing broader extinction risk assessments. This study, therefore, aims to integrate these indices to answer two ecological questions: (1) What is the conservation status of BFMS and KSNR? (2) What do the conservation values indicate about the ecological resilience and priorities for future conservation efforts?

2 Materials and methods

2.1 Study area

The study was conducted in Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR), located in the forest-savannah transition zone of Ghana (Fig. 1). These sites are characterised by dry semi-deciduous vegetation and are designated wildlife-protected areas under the management of the Wildlife Division (WD) of the Ghana Forestry Commission. The local community also plays an important role in the management of the BFMS.

BFMS, located in the Kintampo Forest District, receives an average annual rainfall ranging from 800 to 1200 mm and experiences a bimodal rainfall pattern, with minor rains from September to November and a primary rainy season from March to June. The mean annual temperature is approximately 26°C. Geographically, the sanctuary lies between longitudes 1° 41′ 10" W to 1° 42′ 15″ W and latitudes 7° 41′ 30" N to 7° 43′ 33″ N, covering an area of about 535 hectares (ha) (Amankwah et al. 2021). Senya, Akrudwa Payin, Akrudwa Kuma, Busunya, Bomini, Bonte, and Kokrompe are towns surrounding Boabeng-Fiema. The forest of the sanctuary is home to diverse flora and fauna, including three species of primates: *Colobus vellerosus*, *Cercopithecus campbelli lowei* and *Galago senegalensis* (Saj et al. 2006). The *C. vellerosus* primate is catalogued as Critically Endangered on the IUCN Red List of threatened species. Two rivers, Beten and Daworo,

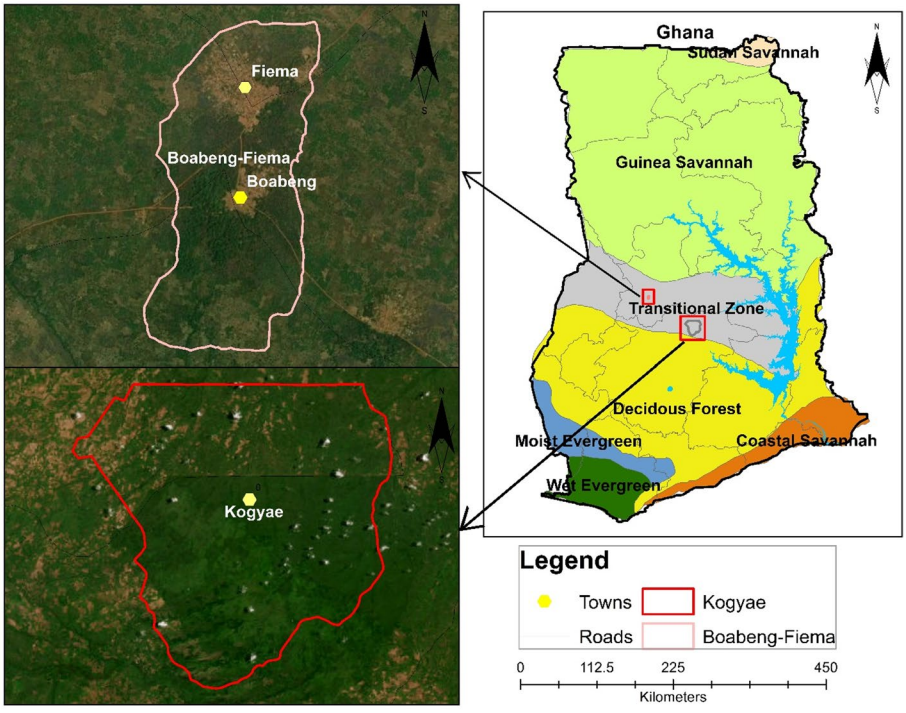


Fig. 1 Vegetation map of Ghana showing the geographical location of the Boabeng-Fiema Monkey Sanctuary (BFMS, top) and Kogyae Strict Nature Reserve (KSNR, bottom), the two study sites located within the forest-savannah transition zone of Ghana

traverse the sanctuary. BFMS lies at an elevation of 321 to 396 m (m) above sea level. The sanctuary doubles as an ecotourism site.

KSNR, which is under the Mampong Forest District of Ghana, spans an area of 33,000 ha and is situated between 7° 14′ N and 1° 05′ W (Afriyie et al. 2021; Janssen et al. 2018). Oku, Congo, Kyeiase, Dome, Aframso, Ejura and Drobonso are towns surrounding KSNR (Ayivor et al. 2020a, b). The reserve is a habitat for mammal species, including buffalo, kob, waterbuck and bushbuck, as well as primate species, such as the putty-nosed monkey and King Colobus (*Colobus polykomos*), that are listed as endangered on the IUCN Red List (Afriyie et al. 2021; Janssen et al. 2018). KSNR experiences distinct dry and rainy seasons, with peak rainfall occurring in June and September and an average annual precipitation of 1,269 mm. The mean annual temperature is 27 °C (Armani et al. 2018). The reserve's average elevation is 180 m above sea level. Classified under IUCN Category 1a, indicating that it is strictly designated for scientific research (Ayivor et al. 2020a, b; Janssen et al. 2018). The vegetation of KSNR plays an important role in protecting the tributaries of the Afram River (Boakye et al. 2017).

2.2 Data collection

2.2.1 Plot design and vegetation sampling

A nested plot design was employed to facilitate comprehensive and systematic data collection across the two study sites. Land Use and Land Cover Classes (LULCC) that were considered are closed forest (continuous canopy covering at least 60% obstructing sunlight from reaching the forest floor), open forest (discontinuous canopy cover ranging between 15 and 59%), woodland (WL, scattered trees or shrubs with grass layer), savannah (dominated by a continuous layer of grass with few to no trees) and cropland (areas under cultivation). Food and Agriculture Organization (FAO) forest inventory guidelines recommend the use of nested plot designs across land cover classes to improve ecological representation at multiple scales (FAO 2017). In line with these guidelines, the study established five main plots for each LULCC, resulting in 25 main plots per site and a total of 50 main plots across Boabeng-Fiema Monkey Sanctuary (BFMS) and Kogyae Strict Nature Reserve (KSNR). This sampling intensity aligns with protocols proven to be sufficient for capturing species diversity and composition in comparable ecological studies (Asare et al. 2020; Dibaba et al. 2019).

Each main plot measured 30 m × 30 m, in alignment with standard forest inventory protocols for tropical forests. This plot size ensured sufficient spatial representation of woody species diversity while balancing logistical feasibility and sampling effort (Arasa-Gisbert et al. 2024; Djagbletey et al. 2018; Searle and Chen 2017). Within each main plot, three subplots of 10 m × 10 m were established along a diagonal transect; one centrally located and the other two positioned towards opposite corners of the main plot. This subplot arrangement resulted in a total of 75 subplots per site and 150 subplots across both sites. Consequently, the study comprised 100 plots per site (25 main plots + 75 subplots), totalling 200 plots across the two sites. All woody species within both the main and subplots were identified to the species level.

2.2.2 Integration of remote sensing and spatial analysis

Although the current study's primary objective was to assess conservation value using species-based indices, it builds upon prior research that employed remote sensing and

GIS techniques to analyse spatial trends in forest degradation, land cover change and carbon stock dynamics. Specifically, Amankwah et al. (2021) conducted a multi-temporal land cover classification of BFMS using satellite imagery from 1992 to 2018. The forest was classified into six LULC types—closed forest, open forest, savannah woodland, savannah, farmland, and built-up areas—and significant trends were observed, including a marked decline of 242.19 ha in closed forest and increases in open forest, built-up areas and croplands. These changes were associated with anthropogenic pressures such as farming and charcoal production.

Further, Amankwah et al. (2024) assessed spatiotemporal changes in carbon stock across BFMS and KSNR using Landsat imagery, field measurements and allometric models. The study quantified losses in carbon stocks from 1992 to 2023, revealing total carbon losses of 40,236 Mg C in BFMS and 272,109 Mg C in KSNR, primarily due to activities such as bushfires, charcoal production, and agricultural encroachment.

These spatial analyses provided a foundation for understanding the ecological context and degradation history of the study areas and informed the selection of sampling locations in the current research. As such, spatial degradation, land cover transitions and anthropogenic impacts were already accounted for in earlier phases of the research. The current study complements these findings by applying conservation indices to evaluate the ecological health and conservation priority of the remaining forest fragments, providing a more holistic perspective on landscape resilience.

2.3 Data analysis

To assess the conservation status of the two protected areas, the study employed the Genetic Heat Index (*GHI*) and Red List Index (*RLI*) that provide bioquality insights regarding species endemism and threat levels. These indices are valuable tools for prioritising conservation efforts, as they quantify species rarity, extinction risk and conservation significance (Marshall et al. 2016; Owusu et al. 2022).

The GHI (Eq. 1), developed under the IUCN forest conservation programme by Hawthorne and Abu-Juam (1995) and Hawthorne and Gyakari (2006), evaluates endemism by assigning star ratings to species based on rarity (Djagbletey et al. 2021). A higher GHI value indicates the presence of many geographically restricted (endemic) species, whereas a lower GHI suggests that species are more widely distributed. The GHI was calculated by assigning each species a star rating, which represents a category of global rarity, with corresponding weight (Table 1) (Djagbletey et al. 2021; Hawthorne and Abu-Juam 1995; Hawthorne and Gyakari 2006; Owusu-Prempeh et al. 2018). Sites with 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 (Owusu-Prempeh et al. 2018).

$$GHI = \frac{(GD \times GDweight) + (GN \times GNweight) + (PK \times PKweight) + (RD \times RDweight) + (ST \times STweight) \times 100}{GD + GN + PK + RD + ST} \quad (1)$$

Table 1 Weight and comments on the star rating of species (Table adapted from Hawthorne and Abu-Juam (1995) and Hawthorne and 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 trees 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

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. GDweight (GNweight etc.) = weight of Gold (Green etc.) Star species.

To complement the GHI, the RLI (Eq. 2) was applied to reflect species' extinction risk, based on IUCN threat categories (Butchart et al. 2007). The RLI is calculated using weighted values assigned to each IUCN category, where lower index values indicate higher extinction risk.

$$RDI_t = 1 - \frac{\Sigma\, {}_s W_{c\,(t,s)}}{(W_{EX} * N)} \tag{2}$$

Where *Wc(t, s)* is the weight for category (*c*) at time (*t*) for species (*s*) (the weight for 'Critically Endangered' = 4, 'Endangered' = 3, 'Vulnerable' = 2, 'Near Threatened' = 1, 'Least Concern' = 0. 'Critically Endangered' species tagged as 'Possibly Extinct' or 'Possibly Extinct in the Wild' are assigned a weight of 5); WEX = 5, the weight assigned to 'Extinct' or 'Extinct in the Wild' species; 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.

3 Results and discussion

3.1 Woody species composition of the protected areas

A total of 1094 individual trees were sampled in the study area, with 681 individuals recorded in BFMS and 413 in KSNR. Species composition analysis revealed that the majority of the woody species were native species of high economic and ecological value. Notably, the closed and open forests emerged as hotspots for the top species identified within the protected areas (Figs. 2 and 3), emphasising the importance of intact habitats for biodiversity conservation.

The dominance of species, such as *Anogeissus leiocarpus*, *Daniellia oliveri* and *Pterocarpus erinaceus*, valued for their medicinal properties, highlights the important ecosystem services these forests provide and their contribution to local livelihoods (Appiah 2013). These dominant species are well adapted to dry conditions and prolonged dry seasons, thereby contributing to the resilience of the forests (Chen et al. 2023). Biodiversity conservation enhances the resistance and resilience of forest and savannah ecosystems to climate extremes and contributes to soil conservation (Isbell et al. 2015).

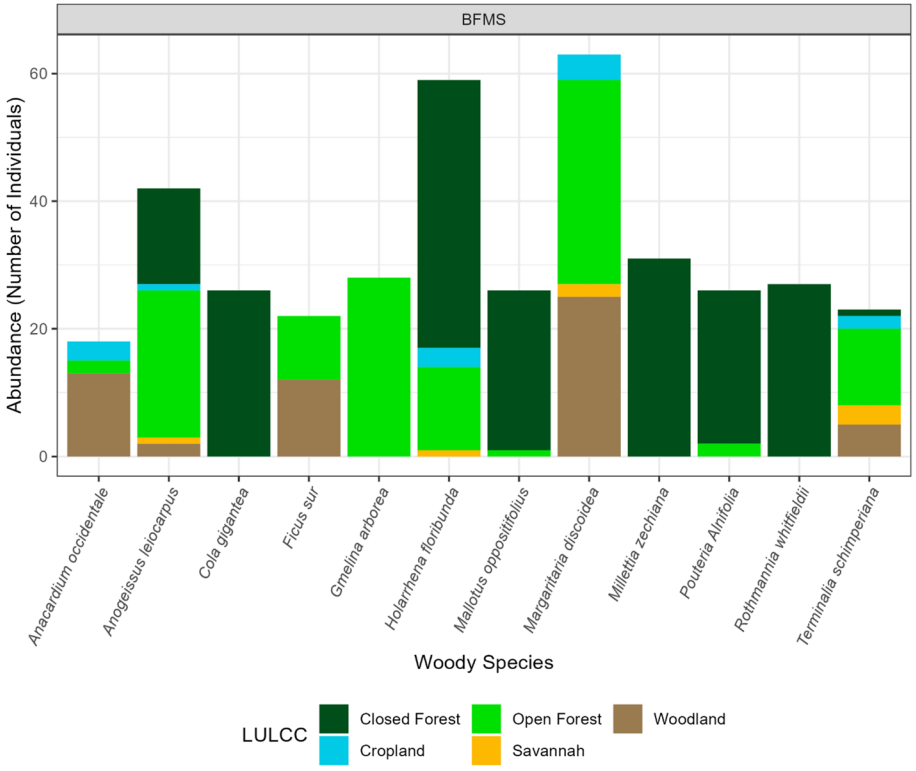


Fig. 2 Top 12 species across the different LULCCs in Boabeng-Fiema Monkey Sanctuary

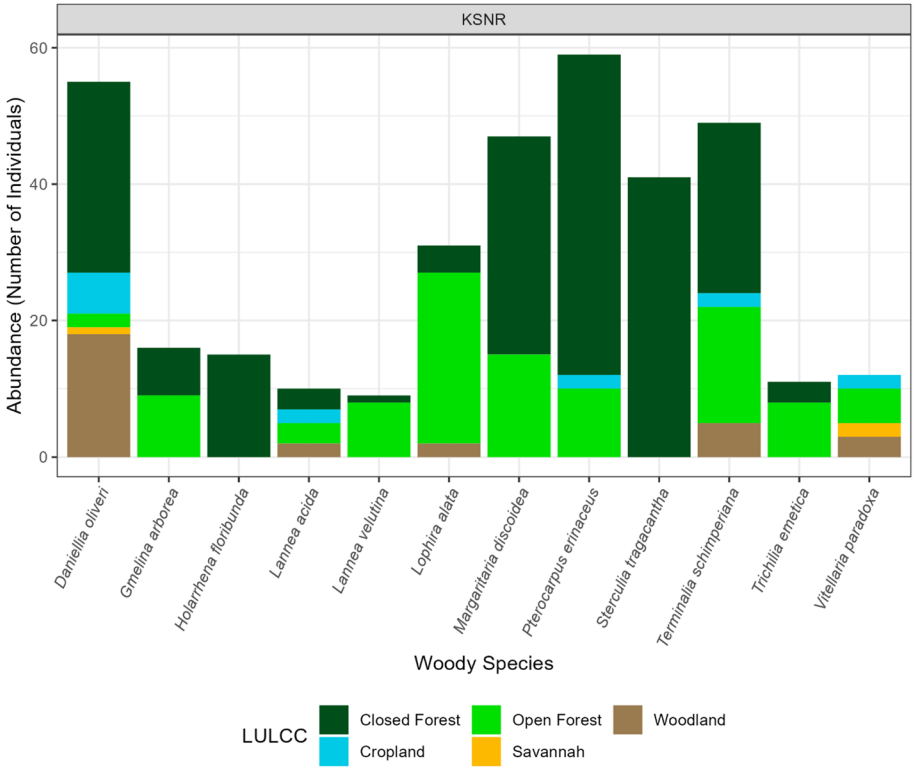


Fig. 3 Top 12 species across the different LULCCs in Kogyae Strict Nature Reserve

The identification of exotic species, *Anacardium occidentale* (cashew) and *Gmelina arborea* (Gmelina), within the protected areas suggests historical land-use disturbances. These species, often introduced for plantation, agricultural and timber purposes, reflect anthropogenic pressures that may have altered the native vegetation dynamics (Akyereko et al. 2022). Exotic species often outcompete native species for resources, potentially reducing biodiversity and modifying soil properties, hydrological processes and habitat structures (Cochard 2011). This finding aligns with previous studies documenting agricultural encroachments in the protected areas (Ayivor et al. 2015; Janssen et al. 2018).

3.2 Genetic heat index of the protected areas

Each species was categorised into its respective colour codes (star rating) based on its rarity at both national and international levels, degree of endemism and ecological and taxonomic characteristics (Fig. 4). These ratings were subsequently analysed to obtain the GHI values. The Genetic Heat Index (GHI) values recorded for BFMS (134.24) and KSNR (105.41) indicate that both sites possess considerable conservation value. According to the categorisation system proposed by Owusu-Prempeh et al. (2018), sites with GHI values above 100 are regarded as biologically rich, ecologically significant and important for the preservation of biodiversity.

The star rating further signifies the importance of these protected areas in national conservation strategies, particularly in regions experiencing increasing anthropogenic pressure such as agricultural expansion, illegal logging and land-use change. The GHI values align with the areas' designation as key biodiversity areas and support arguments for increased investment in their management and restoration efforts (Oduro et al. 2012). In this regard, BFMS and KSNR not only conserve biodiversity locally but also

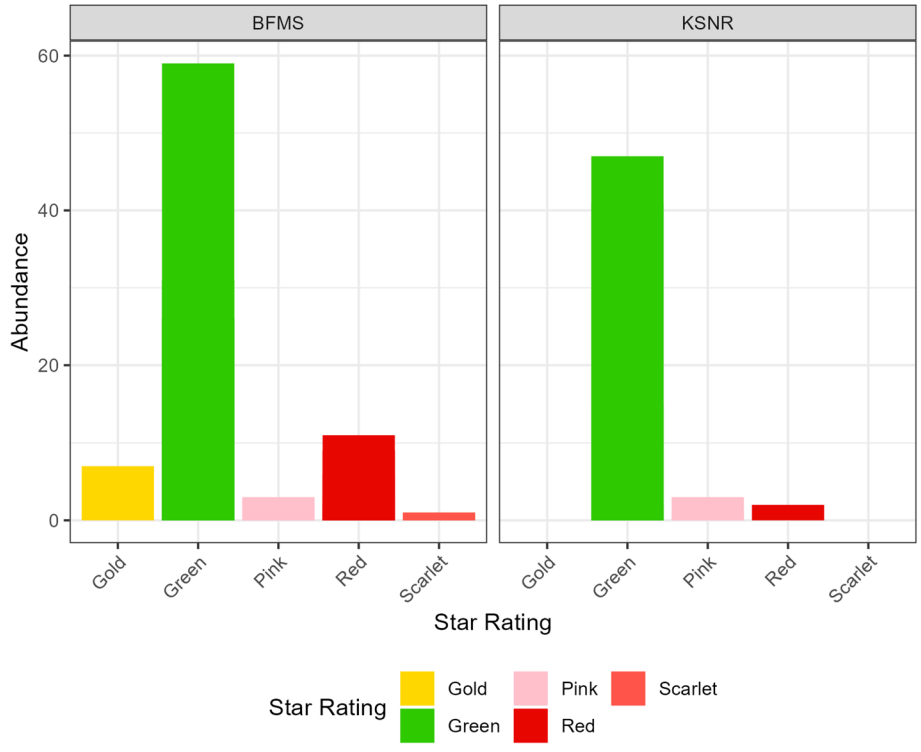


Fig. 4 Star rating of woody species in the protected areas

advance 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).

3.3 Red list index of the protected areas

The vegetation of BFMS and KSNR is a habitat for woody species ranked as near threatened, vulnerable and endangered on the International Union for Conservation of Nature (IUCN) Red List (IUCN 2025) (Table 2). The identification of these species within the study area highlights the role that these protected areas play in the global conservation of biodiversity, especially for species that are heavily exploited for timber and other economically valuable products (Rees et al. 2023). For instance, *Afzelia Africana* and *Khaya senegalensis*, vulnerable species in both BFMS and KSNR, are known for their high-quality timber and have been extensively harvested in many parts of West Africa (Bandoh et al. 2016). Similarly, *Vitellaria paradoxa*, listed as vulnerable, 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 (Choungo Nguekeng et al. 2021). Its presence underlines the need for their conservation to ensure the sustainability of these important ecological and economic services.

The RLI value typically ranges between 0 and 1. A value closer to 1 indicates that most of the species in the ecosystem are categorized as 'Least Concern' whereas a value closer to 0 indicates that most of the species in the ecosystem are at high risk of extinction. Woody species identified in the study area were ranked according to the IUCN Red List categories (Fig. 5) and the corresponding RLI values were subsequently evaluated. The RLI values of BFMS and KSNR were 0.21 and − 1.55, respectively. The low RLI value of BFMS suggests the sanctuary harbours species at a considerable risk of extinction, emphasizing the need for biodiversity conservation and restoration efforts.

The unexpected negative RLI value for KSNR is primarily attributed to the dominance of *Pterocarpus erinaceus* (commonly known as Rosewood; Fig. 3), an Endangered Species on the IUCN Red List with a high threat weighting, which was also the most abundant woody species recorded in the reserve. The predominance of *P. erinaceus* substantially influenced the RLI value. Although a negative RLI value is generally considered outside the normal range, such outcomes have been reported under specific circumstances. As

Table 2 Woody species identified at Boabeng-Fiema monkey sanctuary (BFMS) and Kogyae strict nature reserve (KSNR) classified as Vulnerable, near threatened and endangered by the IUCN red list index (RLI)

Species	IUCN rating	Site
Afzelia africana	Vulnerable	BFMS and KSNR
Albizia ferruginea	Near Threatened	BFMS
Antrocaryon micraster	Vulnerable	BFMS
Entandrophragma candollei	Vulnerable	BFMS
Khaya grandifoliola	Vulnerable	BFMS
Khaya senegalensis	Vulnerable	BFMS and KSNR
Lophira alata	Vulnerable	BFMS
Milicia excelsa	Near Threatened	BFMS
Nesogordonia papaverifera	Vulnerable	BFMS
Pterocarpus erinaceus	Endangered	KSNR
Vitellaria paradoxa	Vulnerable	KSNR

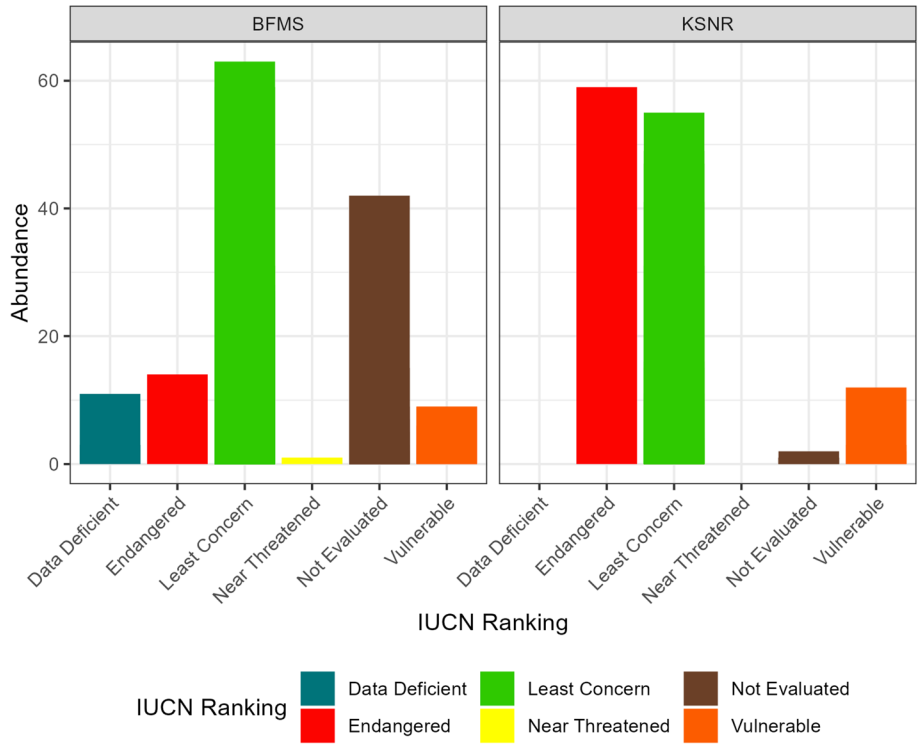


Fig. 5 IUCN ranking of species in protected areas

noted by Butchart et al. (2007), in localised assessments, such as KSNR, where species with high threat weights are dominant, the RLI can yield values below zero. This result emphasises the importance of integrating species abundance with extinction risk categories to provide a more comprehensive understanding of ecosystem health and conservation priorities.

Pterocarpus erinaceus is among the most heavily exploited tree species in West Africa, primarily due to the high value of its timber. Unsustainable and illegal harvesting practices have resulted in a significant decline in its populations, with approximately 80% of global Rosewood trade originating from this region (Baidoo et al. 2023). In response to this threat, the Ministry of Lands and Natural Resources of the Government of Ghana imposed a complete ban on the harvesting and trade of Rosewood in 2019. However, illegal exploitations persist, posing a serious challenge to the recovery of the species (Kansanga et al. 2021). The negative RLI value recorded for KSNR 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.

3.4 Implications for biodiversity conservation and management

The conservation status assessment of the protected areas provides compelling evidence for the continued support and enhancement of conservation efforts in these ecosystems. The presence of species ranked as Vulnerable, Near Threatened and Endangered according to the IUCN Red List emphasises the urgent need for sustained and strategic interventions.

Effective conservation of these protected areas has far-reaching implications, not only for maintaining species diversity but also for supporting broader ecosystem functions essential for climate change mitigation and adaptation (Boakye et al. 2017; Subashree et al. 2021). Forests dominated by diverse and ecologically significant species act as major carbon sinks, sequestering substantial amounts of atmospheric carbon dioxide and contributing to global efforts to combat climate change (Adu-Bredu et al. 2021; Amankwah et al. 2024). Protecting these ecosystems therefore extends beyond biodiversity conservation to securing climate stability, safeguarding water resources and promoting soil fertility.

In the context of climate change, maintaining and enhancing the ecological integrity of protected areas like BFMS and KSNR is fundamental. Forests that retain high species richness and structural complexity are generally more resilient to climate extremes, such as droughts, floods and fires (Liu et al. 2018; Yadav et al. 2022). Thus, conserving biodiversity not only preserves species for their intrinsic value but also strengthens ecosystem resilience, supporting both human and natural systems in adapting to a changing environment.

3.5 Challenges to conservation governance and enforcement

Despite the clear ecological importance and legal protection status of BFMS and KSNR, ongoing threats such as illegal logging, agricultural encroachment, and unsustainable resource exploitation continue to undermine conservation efforts. These persistent pressures can be attributed to several governance and institutional challenges. Key issues include the lack of involvement of all stakeholders in conservation efforts and policy-making, policies that do not sufficiently favour local communities, resource exploitation by local populations and insufficient funding (Ayivor et al. 2020a, b). Furthermore, Oduro-Ofori et al. (2015) and Ayivor and Ntiamoa-Baidu (2015) noted that the retirement of staff at KSNR without adequate replacements has hindered effective forest management, highlighting the urgent need for staff capacity enhancement and better equipment. Additionally, community engagement and benefit-sharing mechanisms are often inadequate, reducing local incentives to support conservation or actively participate in protection efforts (Agyei-Ohemeng et al. 2021). Without addressing these socio-political and institutional challenges, the ecological integrity of BFMS and KSNR remains vulnerable, threatening not only biodiversity but also the ecosystem services these areas provide. Strengthening governance frameworks, increasing law enforcement resources, promoting transparency, and enhancing community involvement are thus critical steps to complement existing legal protections and ensure the long-term sustainability of these vital ecosystems.

4 Conclusion and way forward

4.1 Conclusion

The Genetic Heat Index values of BFMS (134.24) and KSNR (105.41) highlight the substantial ecological importance of these forests. The Red List Index values of BFMS (0.21) and KSNR (-1.55) indicate an urgent need for conservation action, particularly in KSNR, where the presence of threatened species suggests a heightened risk of biodiversity loss without prompt intervention. These findings underscore the need for targeted

conservation strategies to mitigate anthropogenic disturbances and sustain biodiversity in these protected areas.

4.2 Recommendations for conservation and management

The following recommendations outline key strategies to enhance conservation efforts, promote ecosystem resilience and mitigate anthropogenic threats.

1. Strengthening in-situ conservation: Management interventions should prioritize protecting species of high conservation concern, restoration of degraded habitats and mitigation of anthropogenic threats such as deforestation and habitat fragmentation.
2. Community-based conservation initiatives: Engaging local communities in sustainable forest management practices can enhance conservation efforts and ensure long-term forest protection.
3. Strengthening law enforcement and monitoring systems: There is a need for stronger enforcement of conservation policies, implementation of effective monitoring systems and active measures to curb illegal activities such as logging and poaching.
4. Genetic studies for conservation and restoration: Assessing the genetic diversity and adaptive potential of key species will guide conservation planning and restoration efforts, ensuring that species are resilient to future environmental changes.

By implementing these measures, conservation strategies can be tailored to sustain biodiversity, enhance ecosystem resilience and mitigate ongoing threats to these ecologically significant forests.

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Author contributions
1.A.A.A. – corresponding author, writing of paper, securing funding, visualization. 2. S.P. – supervisor, review of paper, visualization, analysis. 3.E.K.K. - supervisor, review of paper, visualization, methodology. 4.J.A.Q-B - supervisor, review of paper, visualization. 5.S.A-B - supervisor, review of paper, visualization, conceptualization.

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Data availability
The data supporting the findings of this study will be made available by the corresponding author upon reasonable request.

Declarations

Ethical approval
Not applicable. This study did not involve human participants or animal experiments requiring ethical approval.

Consent to participate
Not applicable. No human participants were involved in this study.

Consent to publish
All authors consent to the publication of this manuscript.

Competing interests
The authors declare no competing interests.

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