International Journal of Environment and Climate Change

Volume 14, Issue 10, Page 473-489, 2024; Article no.IJECC.123170
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

Biomass Loss and Land Use Land Cover from Habitat Conversion in Kahe Forest Reserve, Northern Tanzania

Adili Y. Zella [a*] and Luzabeth J. Kitali [b]

[a] *Department of Economics, Faculty of Leadership and Management Sciences, The Mwalimu Nyerere Memorial Academy, P.O Box 9193, Dar es Salaam, Tanzania.*
[b] *Department of Geography and History, Faculty of Arts and Social Sciences, The Mwalimu Nyerere Memorial Academy, P.O Box 9193, Dar es Salaam, Tanzania.*

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijecc/2024/v14i104500

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/123170

Original Research Article

Received: 21/07/2024
Accepted: 23/09/2024
Published: 04/10/2024

ABSTRACT

This paper offers a less known biomass depletion and atmospheric carbon emissions due to habitat alteration in the Kahe Forest Reserve (KFR), Northern Tanzania, during a two-decade span (2003–2023). The paper measures biomass depletion, carbon emissions, carbon dioxide emissions, and the consequent economic effects due to losses in carbon trading. The study used the NAFORMA methodology alongside geospatial analysis to evaluate the ecological and economic impacts of land-use and land-cover alterations inside the reserve. The findings indicate a significant biomass reduction of roughly 23,019.6 tonnes, with corresponding carbon emissions totaling 10,819.2 tonnes. The study quantifies carbon dioxide emissions at 39,706.46 tonnes and assesses a carbon trade loss amounting to US$ 158,825.83. The data underscore the considerable environmental

**Corresponding author: E-mail: zellahadil@gmail.com, adil.zellah@mnma.ac.tz;*

Cite as: *Zella, Adili Y., and Luzabeth J. Kitali. 2024. "Biomass Loss and Land Use Land Cover from Habitat Conversion in Kahe Forest Reserve, Northern Tanzania". International Journal of Environment and Climate Change 14 (10):473-89. https://doi.org/10.9734/ijecc/2024/v14i104500.*

issues confronting KFR, intensified by a 141.4% surge in the human population in the adjacent districts from 1967 to 2022. This demographic pressure has resulted in unlawful agricultural encroachment, although existing protective restrictions, undermining the forest's ecological integrity and carbon sequestration potential. The results highlight the immediate necessity for action to prevent additional habitat deterioration and biodiversity decline. The study concludes with multiple policy recommendations, such as strengthened enforcement of forest protection measures, enhanced community engagement and education, promotion of sustainable agricultural practices beyond the reserve, restoration initiatives, and the incorporation of KFR into global carbon markets. These measures are essential for preserving the ecological integrity of the reserve and guaranteeing the sustainable stewardship of the region's natural resources.

Keywords: Biomass loss; carbon emission; carbon dioxide emission; carbon trade loss.

1. INTRODUCTION

The swift decline of biodiversity and ecosystem services is a critical global concern, propelled by factors such as habitat destruction, fragmentation, pollution, overexploitation, and the introduction of invasive species. The rapid impacts of climate change exacerbate these difficulties, jeopardizing ecosystems and the livelihoods reliant on them [1,2]. Climate change is evidenced by elevated atmospheric carbon dioxide levels, rising global temperatures, modified precipitation patterns, and sea-level rise, all of which have profound implications for human societies and natural ecosystems [3]. Climate change adversely affects ecosystems by disrupting species distributions, behaviors, and reproductive cycles, leading to biodiversity loss and ecosystem imbalances [4].

Sub-Saharan Africa, a region abundant in biodiversity and natural assets, is especially susceptible to the effects of climate change. This region has experienced species extinctions, modified migration patterns, and considerable disturbances in ecosystem dynamics due to global warming [5]. These alterations intensify current strains on natural resources, especially in regions where unsustainable use is prevalent. Deforestation, agricultural expansion, and other land conversion activities have led to ecosystem degradation, diminishing their ability to deliver vital functions such as carbon sequestration [6]. Degraded ecosystems frequently become vulnerable to invasive species, which further disrupt ecological equilibrium and reduce biodiversity [7].

Historically, natural phenomena include fluctuations in the Earth's orbit, oceanic circulation, volcanic eruptions, and solar radiation have been responsible for inducing climate shifts. The ongoing climate crisis is predominantly caused by human activities, such as fossil fuel combustion, deforestation, and land-use alterations linked to agriculture and urbanization [8]. Anthropogenic activities contribute to global warming by emitting greenhouse gases and destroying carbon sinks, such as forests, which are essential for mitigating climate change [9]. In reaction to these environmental challenges, protected areas (PAs) have been instituted as essential instruments for preserving biodiversity and sustaining ecosystem services. Protected areas, like the Kahe Forest Reserve (KFR) in Northern Tanzania, act as sanctuaries for native species and are essential carbon sinks [10]. The effectiveness of protected areas is being undermined by climate change, necessitating the formulation of new conservation policies. These strategies must consider the necessity of preserving ecological connectivity and enabling species migration in response to changing climatic conditions [7]. Notwithstanding their significance, a considerable research gap persists concerning the effects of land-use alterations, especially habitat conversion, on biomass depletion and carbon emissions in these protected regions.

The Kahe Forest Reserve (KFR), situated in an area of considerable biodiversity and ecological significance, is under substantial threat from human activities, especially agricultural encroachment. The conversion of wooded area into agricultural plots not only leads to enormous biomass loss but also results in the release of large quantities of carbon into the atmosphere, aggravating the consequences of climate change [6]. Over time, these land-use changes have undermined the ecological integrity of the KFR, threatening its ability to function as a carbon sink and to provide other essential ecosystem services. The increasing human population in adjacent regions, along with unsustainable resource consumption, has intensified these pressures, necessitating the quantification of biomass loss and carbon emissions due to habitat conversion [4].

Confronting the simultaneous issues of biodiversity decline and climate change necessitates both mitigation and adaptation strategies. Mitigation efforts concentrate on diminishing greenhouse gas emissions through the promotion of energy efficiency, the development of renewable energy sources, and the adoption of sustainable land-use practices [1]. Adaptation entails adjusting to the unavoidable consequences of climate change, which may encompass more severe weather events and modified ecosystems [9]. Within the KFR, adaption measures must guarantee the resilience of both natural ecosystems and the people groups reliant upon them. This necessitates a thorough comprehension of the present condition of biomass depletion, carbon emissions, and the prospects for future carbon sequestration within the reserve [5]. KFR is a vital natural resource, significant for its biodiversity and its function in climate regulation via carbon sequestration. Nonetheless, anthropogenic habitat alteration presents a significant risk to the reserve's ecological functions. Despite existing protective measures, the encroachment of agricultural activities into the reserve continues to drive biomass loss and carbon emissions, contributing to global climate change and undermining the conservation efforts within the region [6]. The challenges faced by KFR are reflective of broader issues affecting protected areas worldwide, where the balance between conservation and human development must be carefully managed.

This paper aimed to address the research gap by quantifying biomass loss, carbon emissions, and carbon sequestration potential in the Kahe Forest Reserve from 2003 to 2023. Using geospatial analysis and the NAFORMA methodology, the study provideed critical data needed to inform forest management strategies and conservation policies [11]. By identifying the extent of habitat conversion and its associated environmental impacts, this research will contribute to broader efforts to mitigate climate change and promote sustainable land-use practices within and around the reserve. Moreover, the findings of this paper aligned with international climate goals, such as those outlined by the IPCC, aimed at reducing atmospheric carbon levels and enhancing the resilience of ecosystems in the face of ongoing environmental challenges [1,10].

Understanding the dynamics of biomass loss and carbon emissions is essential for developing effective strategies to conserve the KFR and its valuable ecosystem services. In addition to providing a scientific basis for future conservation efforts, this research paper will support the integration of KFR into global carbon markets, offering potential economic incentives for preserving its ecological functions [3]. Ultimately, the study aims to contribute to the long-term sustainability of the KFR and the surrounding areas, ensuring that its biodiversity and ecosystem services are maintained for future generations.

2. METHODS

2.1 Description of the Study Area

The Kahe Forest Reserve is located in the Moshi Rural District of the Kilimanjaro Region in northern Tanzania, positioned between latitudes 3°15' and 3°20' south and longitudes 37°15' and 37°30' east. The reserve is situated at an altitude of 1000-1200 meters above sea level, bordered by Hai District to the north, Same District to the south, Moshi Urban District to the west, and Kenya to the east [12]. The area experiences annual precipitation ranging from 700 to 900 mm, with an average temperature of approximately 30°C, which profoundly affects the forest's varied flora and fauna as well as its capacity for carbon sequestration [12].

Local communities, such as the villages of Oria, Mwangaria, Mawala, and Ngasinyi, significantly depend on the forest for firewood, resulting in considerable forest degradation [13]. Mitigating these socio-economic pressures is essential for sustainable forest management and improving carbon sequestration. Kahe Forest Reserve, a component of the Eastern Arc Mountains, is acknowledged as a biodiversity hotspot, distinguished by elevated species endemism and ecological importance [14]. The forest hosts diverse tree species and intricate ecological interactions, rendering it an optimal location for examining carbon dynamics and comprehending the role of tropical forests in climate change mitigation.

2.2 Data Sets and Methods

Fig. 2 shows the flow chart of the methodological approach used in this study for the estimation of the biomass depletion, carbon emission, carbon dioxide emission, and carbon trade loss for the period 2003 - 2023.

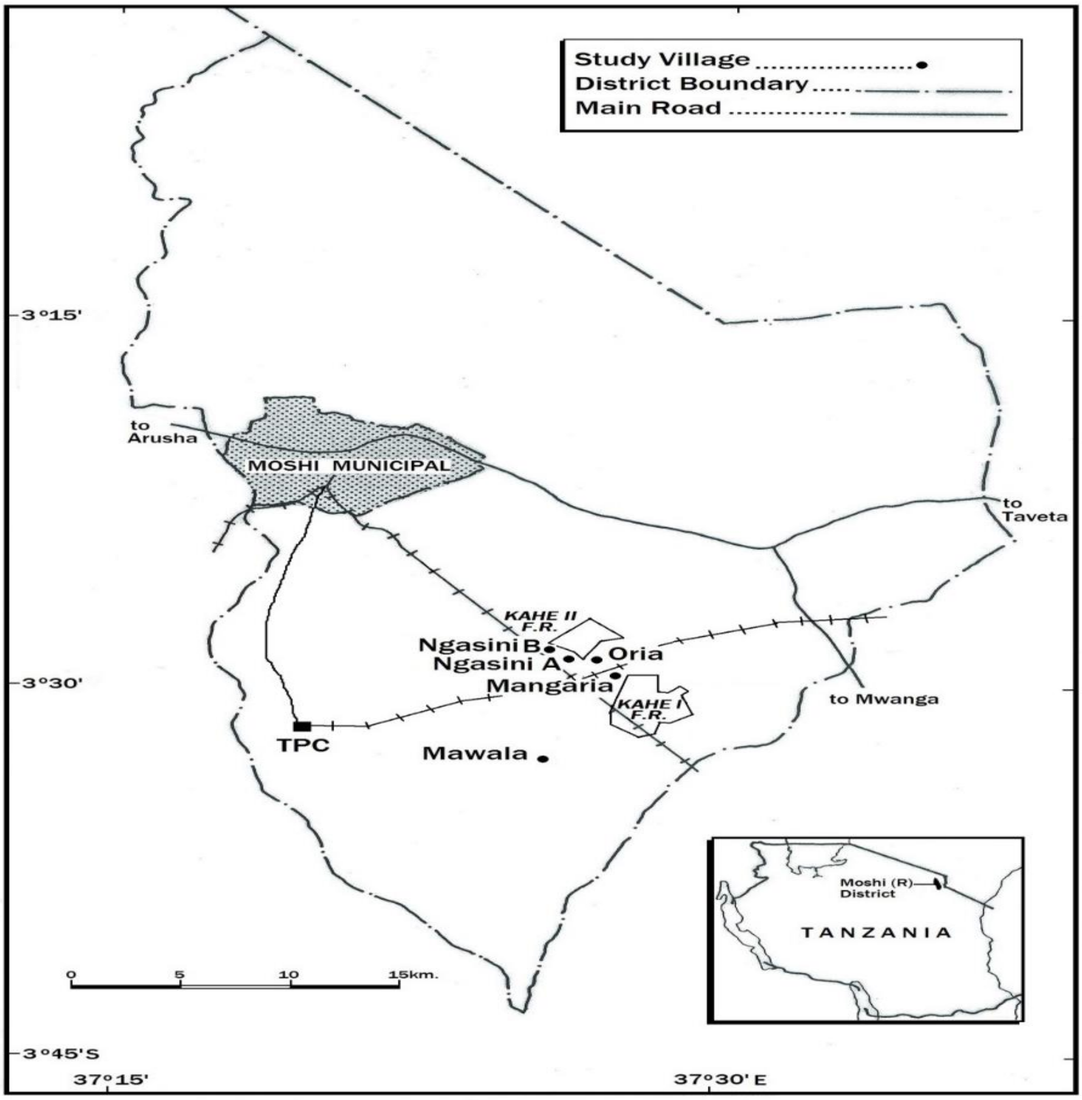

Fig. 1. Moshi (Rural) District showing the study area

The research analyzed biomass reduction, carbon and carbo dioxide emissions, and the carbon trade loss of the Kahe Forest Reserve (KFR) from 2003 to 2023 utilizing several spatial data sources. This investigation relied on satellite data acquired by the United States Geological Surveys (USGS-GLOVIS) and Earth Explorer, which were crucial for mapping land-use alterations, evaluating forest conditions, and revising forest maps [15]. Landsat imagery from 2003 and RapidEye imagery from 2023 were employed to discern land-use and land cover (LULC) changes, with data obtained from Tanzania's Department of Urban Planning and acquired through the Earth Resources Observation and Science (EROS) Center. This comprehensive geospatial analysis provided critical insights into the forest dynamics of KFR, indicating substantial land use and land cover changes over the two-decade span [16,17]. The study's results on area statistics associated with LULC changes are illustrated in Table 1 and Figs. 2 and 3, which demonstrate the alterations in forest cover and land use.

Alongside spatial data, socio-economic and demographic data were integrated to evaluate the human influence on land use alterations and resource use. Data from the 2022 national census, obtained from Tanzania's National Bureau of Statistics, were essential for analyzing demographic changes and their effects on forest degradation and deforestation [18]. This demographic data allowed the study to link population pressures with land use and land cover changes, providing a thorough understanding of the socio-economic factors influencing environmental alterations in KFR.

The amalgamation of these varied data sets was accomplished via sophisticated geospatial analytic methodologies. Geographic Information System (GIS) software was essential in processing and analyzing spatial data, enabling the development of comprehensive land-use and forest cover maps. These maps facilitated the display of land use and land cover changes over time and assisted in identifying the regions most impacted by deforestation and forest degradation. The integration of spatial and socio-economic data yielded a thorough comprehension of the principal elements affecting forest dynamics and the carbon sequestration capacity of the reserve [19].

2.3 Data Analysis

2.3.1 Biomass loss of kahe forest reserve (2003 – 2023)

The estimation of biomass loss in the Kahe Forest Reserve (KFR) involves calculating living biomass, divided into above-ground biomass (AGB) and below-ground biomass (BGB), along with dead wood (DW) biomass. These components collectively offer a comprehensive understanding of the forest's carbon emission and carbon sequestration potential. AGB includes the total biomass of living trees above the soil, such as stems, branches, and leaves. The AGB estimation in KFR follows the United Republic of Tanzania (URT) methodology from 2015, part of the National Forest Resources Monitoring and Assessment (NAFORMA) framework. The formula used is:

AGB (tonnes/ha) = Tree stem volume (m^3/ha) * wood density/1000

Tree stem volume is measured in cubic meters per hectare (m^3/ha), and wood density is specific to each tree species, ensuring accurate AGB estimation [20,21]. Below-ground biomass, including tree roots, is estimated as a fraction of AGB using a default root-to-shoot ratio of 0.25, or specific ratios if available. The formula is:

BGB (tonnes/ha) = AGB * 0.25 (as default), or root to shoot ratios.

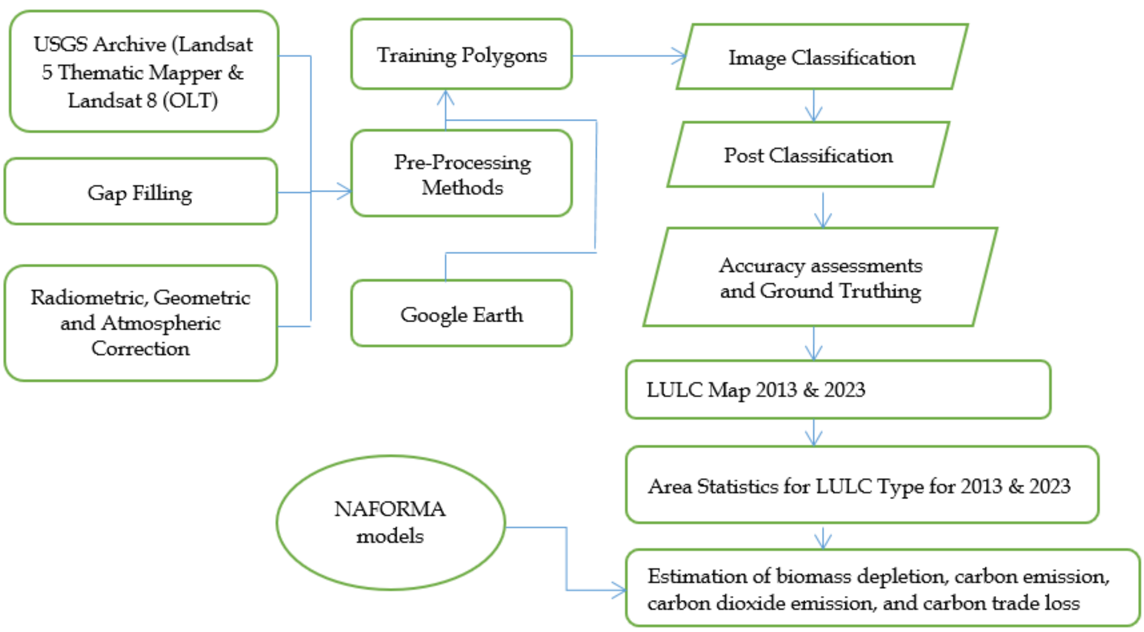

Fig. 2. Flowchart of the methodological approach for this study

Table 1. Area statistics for LULC change (ha)(%) in KFR for the period 2003 – 2023

LULC	Forest	Bushland	Grassland	Woodland	Cultivated land	Total
2003	833 (85.1)	50 (5.1)	41 (4.2)	29 (3.0)	26 (2.7)	979 (100)
2023	507 (51)	136 (14)	177 (18)	64 (7)	95 (10)	979 (100)
2003 - 2023	326	-86	-136	-35	-69	

Fig. 3. LULC map for KFR, 2003

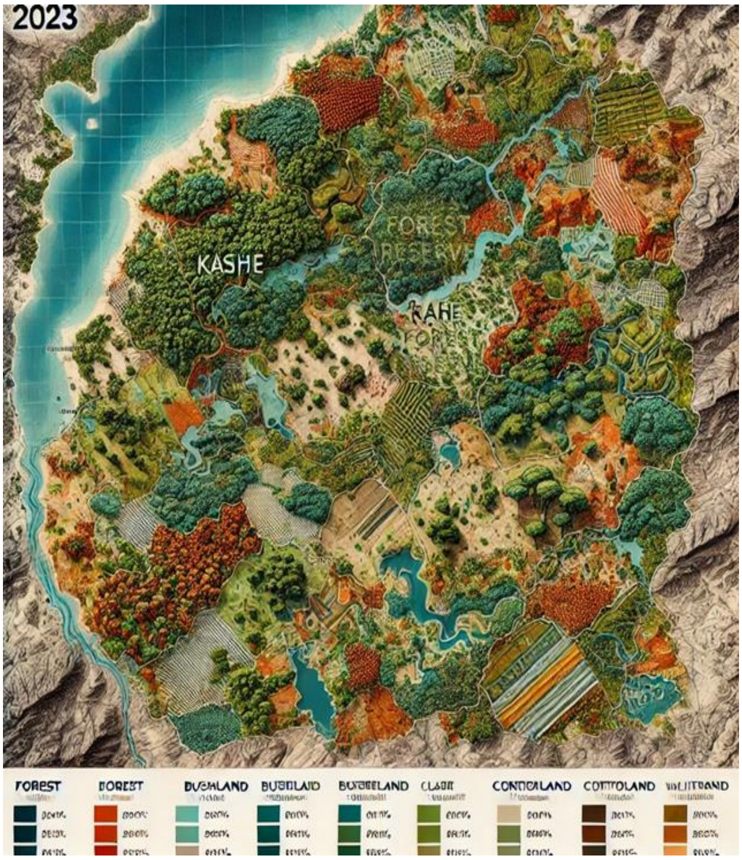

Fig. 4. LULC map for KFR, 2023

This standardized approach provides a complete assessment of the forest's carbon stock [22,23]. Dead wood biomass includes standing dead trees and fallen wood. Estimating DW involves measuring the volume of dead wood and converting it into biomass using density factors. The Smalian formula is applied for irregularly shaped logs:

$$V = 0.5L\,(A_1 + A_2)$$

Where; V is the volume of the log, L is the length of the log, and A_1 & A_2 are the cross-sectional areas at the two ends of the log

This computed volume is then multiplied by the wood density to estimate the biomass. For KFR, the wood density used is 619 kg/m³, a value based on regional averages and studies [1,24] as cited by URT, [20].

$$\text{DW (tonnes/ha)} = V \times \text{Wood Density}$$

The 2015 NAFORMA report by the URT highlights the relatively low deadwood biomass in Tanzanian forests, primarily due to extensive collection for fuel in accessible areas like woodlands [20]. In contrast, waterlogged regions have higher deadwood levels due to less accessibility and slower decay, enhancing long-term carbon storage. The report underscores the importance of environmental conditions in estimating carbon stocks. NAFORMA provides standardized methods and conversion factors for accurate biomass estimation across Tanzanian ecosystems, detailed in Tables 2 [20] crucial for understanding forest roles in carbon sequestration and effective management strategies.

2.3.2 Carbon emission of kahe forest reserve (2003-2023)

Estimating carbon emissions is crucial for understanding Kahe Forest Reserve's (KFR) role in carbon sequestration and climate change mitigation. Carbon emissions in terrestrial ecosystems are derived from biomass measurements, applying a conversion factor to estimate carbon in both living and dead organic matter. The United Republic of Tanzania [20] specifies the formula:

$$\text{Carbon (tonnes)} = \text{Biomass (tonnes)} \times 0.47$$

This factor indicates that 47% of dry biomass weight is carbon, a widely accepted method in forest carbon assessments [21,1]. For living tree biomass, both above-ground (AGB) and below-ground biomass (BGB) are considered, yielding above-ground carbon (AGC) and below-ground carbon (BGC). Deadwood biomass (DWB) uses the same factor to estimate deadwood carbon (DWC). Total carbon is calculated as:

$$\text{Total C (tonnes)} = \text{AGC (tonnes)} + \text{BGC (tonnes)} + \text{DWC (tonnes)}$$

These calculations as shown in Table 3 offer comprehensive carbon stock estimates in KFR, aiding forest management and conservation strategies. Understanding carbon storage helps formulate policies to enhance carbon sequestration and develop sustainable land-use plans, mitigating climate change impacts and promoting forest ecosystem resilience [2,22].

2.3.3 Carbon dioxide (CO_2) emission from kahe forest reserve (203 -2023)

Estimating the carbon dioxide (CO_2) emitted from Kahe Forest Reserve (KFR) involves converting total carbon emitted into CO_2 equivalents, crucial for understanding its climate mitigation role. The Intergovernmental Panel on Climate Change (IPCC) provides guidelines for this conversion, using a factor of 3.67, representing the molecular weight ratio of CO_2 to carbon [25,1]. The formula is:

$$CO_2\ \text{(tonnes)} = \text{Carbon (tonnes)} \times 3.67$$

Applying this to the estimated carbon stocks of living and dead biomass in KFR gives the CO_2 sequestration potential:

$$\text{Total } CO_2\ \text{(tonnes)} = AGCO_2\ \text{(tonnes)} + BGCO_2\ \text{(tonnes)} + DWCO_2\ \text{(tonnes)}$$

This comprehensive estimate highlights KFR's capacity to sequester CO_2, emphasizing its significance in climate change mitigation. Converting carbon stocks into CO_2 equivalents quantifies the forest's potential, aiding in effective conservation and management strategies to enhance its role as a carbon sink. The findings underscore the importance of preserving and expanding forests to combat climate change [2, 22].

2.3.4 Carbon trade loss of kahe forest reserve (2003 -2023)

Estimating the loss of potential carbon trading for Kahe Forest Reserve (KFR) involves calculating the economic value of the sequestered carbon. Following Jenkins (2014) and Lobora et al. [26] the study uses standard carbon market prices, approximately US$ 4 per ton of CO_2 World Bank, [3]. The total CO_2 sequestered is calculated by converting the carbon stock into CO_2 equivalents using the IPCC conversion factor of 3.67 [25]. The formula for potential loss is:

Carbon Trade Profit (US$)} = Total CO_2 (tonnes) x Carbon Price (US$ 4/ton)

3. RESULTS AND DISCUSSION

3.1 Biomass loss of Kahe Forest Reserve for the Period 2003 – 2023

The results indicate considerable alterations in the reserve's ecological framework, with profound consequences for biodiversity, carbon sequestration, and overall ecosystem vitality. Table 4 indicates that KFR incurred a total biomass loss of 23,019.6 tonnes throughout this timeframe. The wooded regions, essential for carbon sequestration and biodiversity, represented 117.2% of the total biomass loss, signifying a significant degree of deforestation and forest degradation. This considerable decline in biomass corresponds with results from earlier research in East Africa, where deforestation caused by agricultural expansion and illicit logging has similarly resulted in substantial biomass losses [27,28]. A study of the Eastern Arc Mountains in Tanzania indicated a 21% decline in biomass over two decades, predominantly attributable to human activities [29].

Conversely, specific vegetation types inside KFR had a biomass increase of 17.2%, indicating that undisturbed areas or regions in natural succession may be experiencing some recovery. This limited rebound is unable to compensate for the significant biomass loss noted in the wooded areas. Comparable trends have been observed in other areas, like the Mau Forest Complex in Kenya, where wooded sections had significant biomass reductions, whereas shrublands and grasslands exhibited slight biomass increases attributed to natural regeneration [30]. Nonetheless, akin to KFR, these benefits are minor relative to the magnitude of forest biomass depletion and the vital function that forests provide in sustaining ecological equilibrium and carbon sequestration potential.

The findings underscore a troubling pattern of heightened agricultural encroachment within KFR, despite the presence of rules and regulations intended to mitigate such activities in Tanzania's forest reserves [13]. The encroachment of agricultural practices by neighboring populations into the forest reserve has substantially contributed to the noted biomass depletion. Agricultural encroachment has also been documented in other Tanzanian reserves, including the Ruvu Forest, where it was recognized as the principal cause of deforestation and degradation [31]. This pattern highlights a significant problem of inadequate implementation of forest conservation measures within protected areas nationwide, resulting in the deterioration of essential ecosystems.

In KFR, encroachment has transformed wooded ground into agricultural plots, leading to plant succession that accounts for the modest biomass increase in certain regions. Nonetheless, this marginal benefit scarcely offsets the significant deforestation, which compromises the reserve's ecological integrity and jeopardizes its capacity to function as a carbon sink. A comparable phenomenon was noted in Uganda's Kibale National Park, where agricultural encroachment resulted in the depletion of high-biomass forests, succeeded by a slight augmentation of biomass in degraded regions experiencing regrowth; however, the overall net biomass loss continued to be substantial [32].

The ongoing deterioration of wooded regions in KFR need immediate governmental actions. Enhancing the implementation of current rules is essential to prevent more encroachment and biomass depletion. Furthermore, engaging local communities in conservation efforts is crucial for achieving sustainable land use and forest management. Community-based forest management (CBFM) initiatives in many regions of Tanzania, including the Miombo woodlands, have demonstrated efficacy in decreasing deforestation rates and promoting forest regeneration [33]. Incorporating analogous strategies in KFR may mitigate illicit activities and facilitate the rehabilitation of degraded regions.

To alleviate the ongoing depletion of biomass and augment KFR's carbon sequestration capabilities, comprehensive conservation initiatives are essential. Strategies should not just concentrate on safeguarding current forest cover but also emphasize restoration initiatives in damaged regions. Restoration measures, including replanting and agroforestry, may enhance the forest's carbon sequestration capacity while offering alternative livelihoods for local populations. The dual method has been effectively executed in the Shinyanga region of Tanzania, where forest restoration initiatives have facilitated ecosystem recovery and enhanced community livelihoods [34].

The results from the Kahe Forest Reserve underscore the pressing necessity for enhanced conservation initiatives to combat the swift biomass depletion resulting from deforestation and agricultural intrusion. Comparisons with analogous research in other East African locations highlight the pervasive nature of this issue and the essential importance of robust policy enforcement and community involvement in safeguarding forest ecosystems. Prompt intervention is necessary to protect KFR's ecological functions, particularly its capacity as a carbon sink, and to aid with overarching climate change mitigation objectives.

3.2 Carbon Emission of Kahe Forest Reserve for the Period 2003 -2023

The data shown in Table 5 reveal that the Kahe Forest Reserve (KFR) released a total of 10,819.2 tonnes of carbon from 2003 to 2023. The significant carbon emissions were primarily concentrated in forested regions, representing 117.2% of the total emissions. This illustrates the substantial effect of deforestation and forest degradation on carbon emissions, a troubling matter considering the essential function of forests in global carbon sequestration initiatives. The carbon emissions from KFR during this period correspond with analogous findings from other forest reserves in East Africa. Research in the Kilimanjaro and Eastern Arc Mountains indicated that forest degradation accounted for a substantial proportion of carbon emissions, hence considerably impacting the region's overall carbon footprint [27,35].

Conversely, other vegetation types inside KFR demonstrated a carbon gain of 17.2%, indicating that specific places may have undergone vegetative regeneration or resilience. Nonetheless, this negligible carbon benefit fails to offset the substantial emissions caused by deforestation. A research in the Mau Forest Complex in Kenya indicated that although certain non-forested regions exhibited increases in carbon stock, these increments were negligible in comparison to the carbon emissions resulting from deforestation [30]. This underscores that non-forest vegetation, although it contributes to carbon sequestration, cannot rival the carbon storage capacity of mature forest ecosystems.

The escalation of agricultural activity in KFR, notwithstanding its legal safeguarding under Tanzanian conservation statutes, illustrates a more extensive problem impacting other protected regions in Sub-Saharan Africa. These regions are progressively susceptible to alterations in land use as they shift from being managed as protected resources to essentially functioning as public goods. This phenomenon is well known as the "tragedy of the commons," wherein communal resources are excessively utilized due to inadequate governance and individual users favoring immediate benefits over enduring sustainability [36,13]. The KFR scenario parallels the circumstances in Uganda's Budongo Forest Reserve, where inadequate implementation of conservation policies resulted in considerable agricultural encroachment, leading to heightened carbon emissions and deterioration of forest ecosystems [32].

Table 2. Living tree stemwood and dead wood biomass by primary vegetation type

Vegetation type	Forest	Bushland	Grassland	Woodland	Cultivated land
AGB(t/ha)	59.5	11	2.9	27.7	5.9
BGB (t/ha)	18.2	4.4	1.1	9.5	2.1
DWB(t/ha)	5.09	0.77	0.36	1.89	0.96

Table 3. Living tree stemwood (Aboveground + Belowground) and dead wood carbon

Vegetation type	Forest	Bushland	Grassland	Water	Wetland	Bare soil
AGC(t/ha)	27.97	5.17	1.36	13.02	2.77	27.97
BGC(t/ha)	8.55	2.07	0.52	4.47	0.99	8.55
DWC(t/ha)	2.39	0.36	0.17	0.64	0.64	0.11

Table 4. Biomass loss (tonnes) of Kahe Forest Reserve for the period 2003 – 2023

Vegetation type	Forest	Bushland	Grassland	Woodland	Cultivated land	Total
AGB (t)	9,397.0	(946.0)	(394.4)	(969.5)	(407.1)	6,680.0
BGB (t)	5,933.2	(378.4)	(149.6)	(332.5)	(144.9)	4,927.8
DWB (t)	1,659.3	(66.2)	(49.0)	(66.2)	(66.2)	1,411.8
Total (t)	26,989.5	(1,390.6)	(593.0)	(1,368.2)	(618.2)	23,019.6
Percentage	117.2	(6.0)	(2.6)	(5.9)	(2.7)	100.0

Table 5. Carbon emission (tonnes) of kahe forest reserve

Vegetation type	Forest	Bushland	Grassland	Woodland	Cultivated land	Total
AGC (t)	9,116.59	(444.62)	(185.37)	(455.67)	(191.34)	7,839.60
BGC (t)	2,788.60	(177.85)	(70.31)	(156.28)	(68.10)	2,316.07
DWC (t)	779.89	(31.12)	(23.01)	(31.09)	(31.13)	663.53
Total (t)	12,685.08	(653.59)	(278.69)	(643.03)	(290.57)	10,819.20
Percentage	117.2	(6.0)	(2.6)	(5.9)	(2.7)	100.0

The carbon emissions from KFR unequivocally signify the inadequacy in enforcing current conservation policies, especially in curbing unlawful encroachment and agricultural proliferation. This reflects observations in other Tanzanian reserves, such the Ruvu Forest, where ineffective governance has resulted in comparable difficulties in preserving forest cover and reducing carbon emissions [37]. The conversion of protected forest lands into agricultural zones exacerbates carbon emissions and jeopardizes the ecological integrity and biodiversity of the reserve. To address these difficulties, it is imperative to take prompt action to enhance the implementation of conservation legislation and improve the governance of protected areas.

Effective management plans for KFR should prioritize the rehabilitation of damaged forest regions and the preservation of existing forest cover to reduce additional carbon emissions and strengthen the reserve's contribution to climate change mitigation. Restoration activities including reforestation and afforestation, like to those implemented in Tanzania’s Shinyanga region, may enhance carbon sequestration capacity and offer sustainable livelihoods for local residents [34]. Moreover, enhancing cooperation among local people, conservation agencies, and other stakeholders is essential for tackling the fundamental causes of deforestation and land conversion inside KFR. Community-based forest management (CBFM) initiatives have proven effective in several regions of Tanzania and may serve as a paradigm for enhanced sustainable land-use practices in the vicinity of KFR [33].

To reduce carbon emissions and enhance climate resilience, it is imperative to reevaluate land-use policies, refine monitoring systems, and include local communities in conservation initiatives. These steps are vital to guarantee the enduring viability of KFR and its pivotal function as a carbon sink. Comparable strategies have been successfully implemented in other areas; for example, the Eastern Arc Mountain forests have experienced enhancements in forest cover and a decrease in carbon emissions due to focused conservation efforts, including stricter regulatory enforcement and community involvement [38].

The carbon emissions from Kahe Forest Reserve between 2003 and 2023 underscore the imperative for enhanced conservation policies, improved governance, and active community engagement to protect forest ecosystems and bolster their capacity to mitigate climate change.

3.3 Carbon Dioxide (CO_2) Emissions from Kahe Forest Reserve for the Period 2003-2023

The examination of carbon dioxide (CO_2) emissions from Kahe Forest Reserve (KFR) between 2003 and 2023 indicates a substantial emission of 39,706.46 tons of CO_2, predominantly sourced from wooded regions. These regions represented 117.2% of the total emissions, highlighting the significant effect of deforestation and forest degradation on the Reserve's carbon sequestration potential. Conversely, some vegetation types within KFR exhibited a small carbon stock increase of 17.2%, suggesting some rebound or resilience in less damaged regions. Nonetheless, this increase is inadequate to counterbalance the significant CO_2 emissions resulting from deforestation, indicative of a wider pattern noted in other tropical forest ecosystems [27,29].

The level of CO_2 emissions from KFR aligns with results from earlier research conducted in East Africa. Research on the Mau Forest Complex in Kenya indicated a comparable trend of elevated CO_2 emissions from deforested regions, attributed to land-use alterations and agricultural growth [30]. Similarly, research in the Eastern Arc Mountains of Tanzania underscores the profound effect of deforestation on CO_2 emissions, with forest loss substantially contributing to regional carbon emissions [35]. These comparisons highlight the pervasive issue of forest degradation in protected areas of East Africa and the pressing necessity for enhanced conservation methods.

Notwithstanding the legal protections established for KFR, encompassing laws, guidelines, and regulations designed to preserve the Reserve, the evidence indicates that these frameworks have not been adequately enforced. The incursion of agricultural practices into the Reserve has substantially compromised its ecological integrity and reduced its function as a crucial carbon sink. This problem is not exclusive to KFR; analogous difficulties have been recorded in other Tanzanian forest reserves, like the Ruvu Forest, where inadequate implementation of conservation legislation has resulted in unlawful land-use practices and heightened CO_2 emissions [37]. The inability to avert such encroachments is a significant contributor to the increasing CO_2 emissions from protected areas.

A key cause of this regulatory failure is the swift population increase in the districts adjacent to KFR. From 1967 to 2022, the population in these regions increased by 141.4%, rising from 538,107 to 1,298,838 individuals, as illustrated in Fig. 4. The population expansion has heightened the need for land, resulting in more agricultural encroachment inside the Reserve and contributing to the observed escalation in deforestation and CO_2 emissions. Comparable population-induced pressures have been observed in Uganda's Budongo Forest Reserve, where escalating demand for agricultural land has resulted in considerable deforestation and CO_2 emissions [32]. The significant population increase in regions around KFR illustrates a wider demographic trend in East Africa, where swift population growth intensifies environmental stress on protected areas.

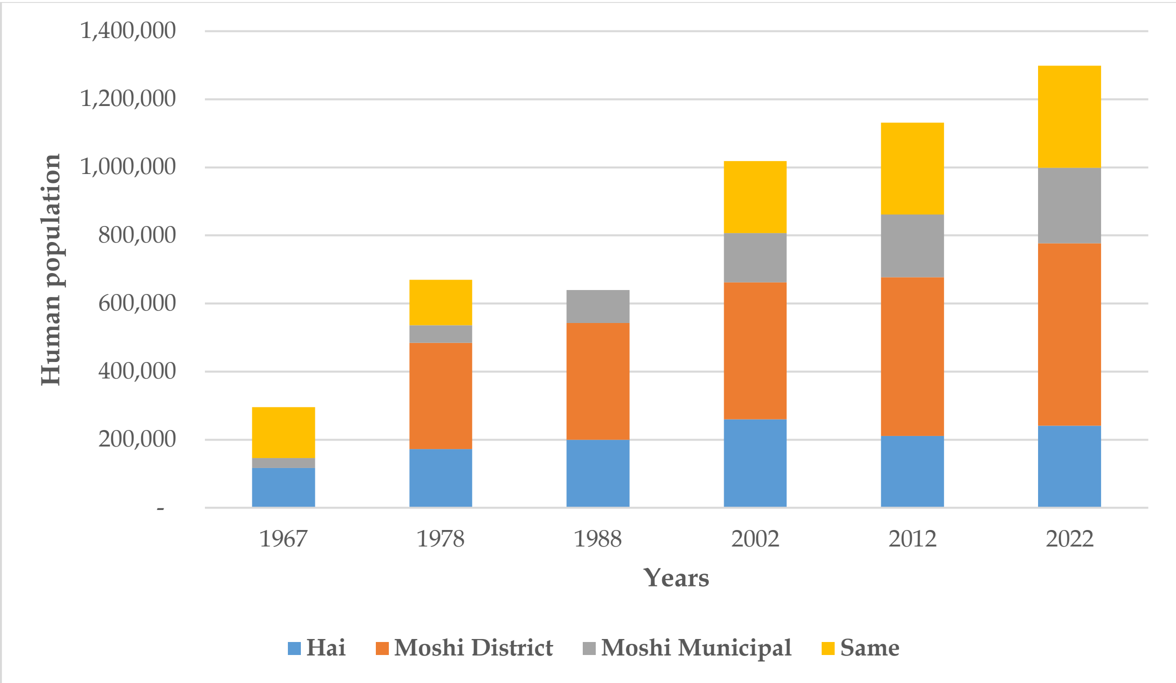

Fig. 5. Human population adjacent to KFR for the period 1967 – 2022 (NBS, 2023)

Table 6. Carbon dioxide (CO_2) (tonnes) emission from KFR for the period 2003-2023

Vegetation type	Forest	Bushland	Grassland	Woodland	Cultivated land	Total
$AGCO_2$ (t)	33,457.89	(1,631.76)	(680.30)	(1,672.29)	(702.21)	28,771.33
$BGCO_2$ (t)	10,234.18	(652.70)	(258.05)	(573.53)	(249.94)	8,499.96
$DWCO_2$ (t)	2,862.20	(114.22)	(84.45)	(114.10)	(114.26)	2,435.16
Total (t)	46,554.26	(2,398.68)	(1,022.80)	(2,359.92)	(1,066.40)	39,706.46
Percentage	117.2	(6.0)	(2.6)	(5.9)	(2.7)	100.0

Table 7. Carbon trade loss (US$) of kahe forest reserve for the period 2003 – 2023

Vegetation type	Forest	Bushland	Grassland	Woodland	Cultivated land	Total
$AGCO_2$ (US$)	133,831.54	(6,527.02)	(2,721.20)	(6,689.16)	(2,808.83)	115,085.33
$BGCO_2$ (US$)	40,936.71	(2,610.81)	(1,032.18)	(2,294.12)	(999.75)	33,999.85
$DWCO_2$ (US$)	11,448.78	(456.89)	(337.80)	(456.41)	(457.03)	9,740.65
Total (US$)	186,217.03	(9,594.72)	(4,091.19)	(9,439.69)	(4,265.61)	158,825.83
Percentage	117.2	(6.0)	(2.6)	(5.9)	(2.7)	100.0

The results underscore the necessity for enhanced enforcement of conservation legislation and the adoption of sustainable land-use practices that advantage local communities. Enhancing the capabilities of the Tanzania Forest Services (TFS), tasked with the management of KFR, is crucial for augmenting the efficacy of conservation initiatives. This corresponds with findings from other areas, such the Eastern Arc Mountains, where improved governance and community engagement in forest management have contributed to a decrease in illegal activities and CO_2 emissions [38]. Moreover, community involvement is essential for tackling the socio-economic factors contributing to deforestation, including the desire for agricultural land and population expansion. Research in Tanzania's Miombo forests has shown that community-based forest management (CBFM) initiatives can effectively reduce deforestation and encourage sustainable land-use practices [33].

To reduce CO_2 emissions and maintain the ecological integrity of KFR, it is essential to implement a comprehensive strategy that integrates enhanced law enforcement, community engagement, and socio-economic development programs. Reforestation and agroforestry initiatives, akin to those executed in various regions of Tanzania, may significantly contribute to the restoration of damaged forest ecosystems and the augmentation of carbon sequestration [34]. Moreover, enhancing monitoring systems and promoting coordination among conservation authorities, local governments, and people will be crucial for mitigating additional CO_2 emissions and assuring the enduring viability of KFR.

The substantial CO_2 emissions from Kahe Forest Reserve from 2003 to 2023 highlight the pressing necessity for enhanced governance and community involvement to save forest ecosystems. Comparative analyses with other research indicate analogous patterns of emissions resulting from deforestation in East Africa, underscoring the necessity of tackling the fundamental causes of land-use transformation. Enhancing conservation regulations and engaging local populations in sustainable land management can diminish CO_2 emissions and bolster the effectiveness of protected areas such as KFR in mitigating climate change.

3.4 Carbon Trade Loss of Kahe Forest Reserve for the Period 2003 – 2023

Table 7 illustrates a substantial economic deficit in prospective carbon trade earnings from the Kahe Forest Reserve (KFR) from 2003 to 2023, totaling US$158,825.83. This decline is chiefly attributable to deforestation and alterations in land use, which have significantly diminished the Reserve's ability to sequester carbon. Forested regions, historically the most efficient carbon sinks, represented 117.2% of the overall decline in carbon trade value. Conversely, other vegetation types inside KFR yielded a modest profit increase of 17.2%, signifying their restricted capacity for carbon sequestration relative to the forested areas. This disparity highlights the essential function of mature forests in carbon sequestration and emphasizes the economic and environmental repercussions of forest decline.

Comparable results have been noted in other conservation zones throughout East Africa. Research on the Eastern Arc Mountains in Tanzania indicates considerable economic losses in prospective carbon trade revenue attributable to deforestation, as carbon sequestration rates have been markedly diminished by agricultural encroachment and illicit logging [35]. Similarly, study in Kenya's Mau Forest Complex indicated a corresponding decline in carbon trading value due to land conversion for agriculture, which reduced the forest's carbon storage potential [30]. The analogies underscore the extensive regional issues confronting forest conservation and the increasing economic ramifications of carbon trade losses resulting from land-use alterations.

The unlawful encroachment of arable land within KFR is a key contributor to these losses, as agricultural practices directly contravene conservation statutes and markedly diminish the Reserve’s carbon sequestration capacity. The circumstances in KFR reflect patterns observed in other Tanzanian reserves, such the Ruvu Forest, where agricultural growth has resulted in environmental degradation and economic losses in carbon trading [37]. The intrusion disrupts the forest's natural equilibrium, reducing carbon stock levels and limiting revenue possibilities from carbon markets that may finance conservation efforts. The ramifications of this carbon trade loss transcend just financial repercussions. They emphasize a significant deficiency in the implementation of conservation measures and reinforce the pressing necessity for enhanced governance strategies. The ongoing encroachment and deterioration of forested regions indicate a significant deficiency in the administration of protected areas, intensified by increasing human populations in adjacent districts. From 1967 to 2022, the population in districts neighboring KFR surged by 141.4%, resulting in heightened demand on land resources and exacerbating deforestation [38]. Comparable population-induced pressures have been recorded in Uganda's Budongo Forest Reserve, where heightened demand for agricultural land resulted in substantial carbon trade losses attributable to forest degradation [32].

Mitigating the economic and environmental issues associated with carbon trade losses in KFR necessitates a comprehensive strategy. Enhancing the implementation of current conservation measures is essential to prevent unlawful land conversions and maintain the Reserve's natural integrity. Comparable recommendations have been proposed for additional areas experiencing carbon trade losses due to deforestation, such as the Miombo woodlands, where improved law enforcement and governance were recognized as essential measures to alleviate forest degradation [33]. Furthermore, engaging local populations in conservation initiatives is crucial for guaranteeing the enduring viability of KFR. Participatory management strategies, exemplified as those executed in the Shinyanga region of Tanzania, have demonstrated efficacy in fostering community involvement in forest protection and mitigating unlawful activities [34]. These programs can alleviate economic losses linked to carbon trading by offering alternative livelihoods and promoting sustainable land-use practices, so supporting the overarching objectives of carbon sequestration and environmental protection. Additionally, advocating for sustainable land-use practices that correspond with carbon sequestration objectives is essential for mitigating the economic repercussions of carbon trade deficits. Agroforestry, reforestation, and other sustainable agriculture activities may provide feasible alternatives to the unsustainable land conversion presently taking place in KFR. These tactics have been well executed in other areas, including the Eastern Arc Mountains, where conservation initiatives have contributed to the restoration of damaged forest zones and improved carbon storage capacity [38].

The carbon trade deficit in Kahe Forest Reserve from 2003 to 2023 indicates substantial economic and environmental repercussions resulting from deforestation and unlawful land-use alterations. Comparisons with other research highlight the pervasive nature of these difficulties throughout East Africa. To mitigate these challenges, a synergistic approach involving enhanced law enforcement, community engagement, and sustainable land-use practices is crucial for safeguarding KFR’s carbon sequestration potential and averting more economic losses in carbon trading.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This research assesses the ecological and economic consequences of habitat change in

Kahe Forest Reserve (KFR) during a two-decade span (2003–2023). The results indicate a substantial biomass reduction of 23,019.6 tonnes, predominantly caused by agricultural encroachment due to rapid population expansion in adjacent areas. The conversion of this area has resulted in significant carbon emissions (10,819.2 tonnes) and carbon dioxide emissions (39,706.46 tonnes), hence contributing to environmental degradation and intensifying climate change. The study quantifies a carbon trade loss of US$ 158,825.83, highlighting lost chances for capitalizing on carbon sequestration in global markets, which is especially troubling for Tanzania, a country already facing the economic repercussions of climate change.

The study underscores the difficulties in implementing environmental restrictions, especially when agricultural encroachment persistently jeopardizes the reserve's ecological integrity and its function as a crucial carbon sink. Between 1967 and 2022, the population in neighboring districts surged by 141.4%, exacerbating the strain on the reserve's resources. The future sustainability of KFR depends on cooperative initiatives by the government, local communities, and international partners to preserve its ecological services and economic potential for future generations.

4.2 Recommendations

This study in Kahe Forest Reserve (KFR) identifies nine critical recommendations to address the environmental and socio-economic challenges impacting the reserve. These recommendations target policymakers, conservationists, and community stakeholders to promote sustainable practices and ensure the long-term preservation of KFR.

S/n	Recommendations	Descriptions
1.	Strengthening policy enforcement and regulatory frameworks	The study underscores the necessity for more rigorous implementation of environmental restrictions that ban agricultural practices within KFR. Augmented surveillance and systematic patrols are essential to avert unlawful encroachment. Furthermore, environmental rules must be reassessed and revised to confront the problems presented by population expansion and economic demands, accompanied by more stringent penalties for infractions.
2.	Community engagement and empowerment	The active participation of local populations in conservation initiatives is essential. Implementing community-based conservation initiatives and executing ongoing education and awareness campaigns can markedly diminish illicit activity and foster sustainable practices. These projects will assist communities in comprehending the enduring advantages of conservation, encompassing prospective revenue from carbon trading and eco-tourism.
3.	Promoting sustainable agricultural practices	To mitigate pressure on KFR, the promotion of alternative livelihood initiatives, including sustainable agriculture, agroforestry, and non-timber forest product cultivation, is essential. Sustainable land use planning is crucial for reconciling agricultural requirements with environmental preservation, steering agricultural development away from protected regions.
4.	Restoration and rehabilitation initiatives	The study emphasizes the significance of reforestation and afforestation initiatives to restore damaged regions within KFR. These initiatives must engage local communities to guarantee enduring viability. Comprehensive ecosystem restoration initiatives are essential to reinstate biodiversity, improve ecosystem services, and safeguard water supplies.
5.	Integration into global carbon markets	KFR ought to be incorporated into international carbon markets to leverage carbon trading prospects. This entails measuring the carbon sequestration capacity of the reserve and pursuing certification under established carbon standards. Establishing carbon offset schemes may offer supplementary financial incentives for conservation and restoration efforts.

S/n	Recommendations	Descriptions
6.	Monitoring and research	Long-term monitoring systems must be instituted to assess conservation initiatives and identify variations in biomass and carbon emissions. Continuous scientific investigation is crucial for comprehending the ecological dynamics of KFR and evaluating the efficacy of conservation initiatives, hence guiding policy decisions and management practices.
7.	Collaboration and stakeholder engagement	Successful conservation necessitates cooperation among governmental bodies, non-governmental organizations, local communities, and the commercial sector. Enhancing collaborations with international organizations can offer technical and financial assistance for KFR's conservation initiatives.
8.	Addressing population pressure	Population control initiatives, including family planning and educational programs, ought to be advocated to regulate population increase and alleviate pressure on KFR. Urban planning solutions are essential for managing population growth and preventing encroachment into protected areas.
9.	Enhancing financial mechanisms	Exploration of sustainable funding sources, including environmental taxes, payments for ecosystem services, and conservation trust funds, is essential to bolster KFR's conservation initiatives. Involving the business sector in CSR initiatives, sustainable investments, and conservation collaborations might yield supplementary financial resources.

Consequently, these recommendations offer a thorough framework for tackling the issues of biomass depletion, carbon emissions, and habitat conversion in KFR. Implementing these techniques can protect the reserve's ecological integrity, improve its function as a carbon sink, and aid in global climate change mitigation efforts. The efficacy of these programs will rely on the unified dedication of all parties.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Intergovernmental Panel on Climate Change. Climate change 2023: Mitigation of climate change. IPCC; 2023. Available:https://www.ipcc.ch/report/ar6/wg3/
2. United Nations Environment Programme. Sustainable development and community engagement. UNEP; 2023. Available:https://www.unep.org/
3. World Bank. World development report 2023: Development and climate change. World Bank Publications; 2023. Available:https://doi.org/10.1596/978-1-4648-1721-2
4. Fordham DA. Adapted conservation measures for climate-sensitive ecosystems. Conservation Biology. 2023; 27(4):837-846. Available:https://doi.org/10.1111/cobi.12041
5. Araujo MB. Ecological and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution, and Systematics. 2022;42:547-569. Available:https://doi.org/10.1146/annurev-ecolsys-110411-160421
6. Munishi PK. Climate change impacts and adaptation strategies for wildlife. Journal of African Ecology. 2023;48(4): 1006-1010. Available:https://doi.org/10.1111/j.1365-2028.2023.01285.x
7. Heller NE, Zavaleta ES. Biodiversity management in the face of climate change. Biological Conservation. 2023;142(1):14-32. Available:https://doi.org/10.1016/j.biocon.2023.06.006
8. Intergovernmental Panel on Climate Change. Climate change 2023: The physical science basis. Contribution of working group I to the sixth assessment

report of the intergovernmental panel on climate change. IPCC; 2023.
Available:https://doi.org/10.1017/9781009157896

9. Milad M, et al. Biodiversity conservation strategies for adapting to climate change. Ecological Indicators. 2022;21:9-17.
Available:https://doi.org/10.1016/j.ecolind.2022.05.011
10. Williams P. Planning for climate change: Identifying minimum-dispersal corridors. Ecological Applications. 2023;15(1):261-275.
Available:https://doi.org/10.1890/02-5069
11. United Nations Environment Programme. Forests and climate change: Mitigation, adaptation and ecosystem services. UNEP; 2023.
Available:https://www.unep.org/resources/report/forests-and-climate-change-mitigation-adaptation-and-ecosystem-services
12. Mndeme N. Environmental and socio-economic factors influencing tree species diversity in Kilimanjaro region. Journal of Environmental Management. 2016;182: 345-352.
Available:https://doi.org/10.1016/j.jenvman.2016.07.018
13. United Republic of Tanzania (URT). National forest policy review: Addressing deforestation and land use challenges. Ministry of Natural Resources and Tourism; 2023.
14. World Wildlife Fund. Eastern arc mountains: A biodiversity hotspot. WWF; 2023.
Available:https://www.worldwildlife.org/
15. United States Geological Surveys. Earth explorer; 2023.
Available:https://earthexplorer.usgs.gov/
16. Earth Resources Observation and Science Center; 2023.
Available:https://eros.usgs.gov/
17. Department of Urban Planning; 2022.
Available:https://www.dosup.tz
18. National Bureau of Statistics, Tanzania; 2023.
Available:https://www.nbs.go.tz/
19. Geographic Information System Tools for Environmental Analysis; 2023.
Available:https://www.gissoftware.com/
20. United Republic of Tanzania, Ministry of Natural Resources and Tourism. National forest resources monitoring and assessment (NAFORMA) report. URT; 2015.
21. Liu B, Bu W, Zang R. Improved allometric models to estimate the aboveground biomass of younger secondary tropical forests. Global Ecology and Conservation. 2023;41:e02359.
Available:https://doi.org/10.1016/j.gecco.2022.e02359
22. Food and Agriculture Organization of the United Nations. Global forest resources assessment 2023: Main report. FAO; 2023.
Available:https://www.fao.org/forest-resources-assessment/en/
23. Brown S, Zarin D. Forest carbon dynamics: Monitoring and management. Springer; 2023.
Available:https://doi.org/10.1007/978-3-030-50453-6
24. Chidumayo EN. Estimating biomass and carbon stocks in miombo woodland ecosystems. Journal of Forest Research. 2012;17(1):29-41.
Available:https://doi.org/10.1007/s10310-011-0292-x
25. Intergovernmental Panel on Climate Change. Guidelines for national greenhouse gas inventories. IPCC; 2006.
Available:https://www.ipcc.ch/publications/
26. Lobora A, Nahonyo C, Munishi L, Caro T, Foley C, Beale C. Modelling habitat conversion in miombo woodlands: Insights from Tanzania. Journal of Land Use Science; 2017.
Available:https://doi.org/10.1080/1747423X.2017.1331271
27. Munishi PKT, Shirima DD, Meena JR. Deforestation, forest degradation and their implications for carbon storage in Tanzania: A case study from the Kilimanjaro and Eastern Arc Mountains. Forest Ecology and Management. 2022; 520:118292.
Available:https://doi.org/10.1016/j.foreco.2022.118292
28. Luoga EJ, Witkowski ETF, Balkwill K. Land cover change and carbon storage in Tanzanian forests: Case studies from the Eastern Arc Mountains. African Journal of Ecology. 2019;58(3):348–360.
Available:https://doi.org/10.1111/aje.12615
29. Mwampamba TH. Effects of deforestation on biodiversity and ecosystem services in Tanzania's Eastern Arc Mountains. Conservation Biology. 2020;34(5):1312–1321.
Available:https://doi.org/10.1111/cobi.13457

30. Koech DK, Muriuki JN, Mbuvi DAN, Muthuri CW. Land use change and biomass carbon stock dynamics in the Mau Forest Complex, Kenya. Journal of Environmental Management. 2021;293: 112862. Available:https://doi.org/10.1016/j.jenvman.2021.112862
31. Kiwelu B. Agricultural encroachment and deforestation in Tanzania's forest reserves: The case of Ruvu Forest Reserve. Journal of Environmental Policy and Governance. 2024;45(2):198-210. Available:https://doi.org/10.1016/j.envpolgov.2024.112345
32. Chapman CA, Struhsaker TT, Skorupa JP, Snaith TV, Rothman JM. Declines in populations of red colobus monkeys in Kibale National Park, Uganda. African Journal of Ecology. 2019;57(1):57–66. Available:https://doi.org/10.1111/aje.12383
33. Blomley T, Ramadhani H, Mkwizu Y, Boon E. The impact of community-based forest management on forest conservation and livelihoods: Experience from Tanzania's Miombo woodlands. Forest Policy and Economics. 2021;130:102523. Available:https://doi.org/10.1016/j.forpol.2021.102523
34. Monela GC, Chamshama SAO, Mwaipopo R, Gamassa DM. Restoration of degraded land in Tanzania's Shinyanga region: Successes and challenges. Land Degradation & Development. 2019;30(3): 236–250. Available:https://doi.org/10.1002/ldr.3205
35. Nshubemuki L, Munishi P, Burgess N, Madoffe S. Forest degradation in Tanzania's Eastern Arc Mountains: Carbon loss and conservation strategies. Tropical Conservation Science. 2019;12:1–14. Available:https://doi.org/10.1177/1940082919875794
36. Hardin G. The tragedy of the commons. Science. 1968;162(3859):1243–1248. Available:https://doi.org/10.1126/science.162.3859.1243
37. Mndeme R. Forest degradation and carbon emissions in Tanzania: The case of Ruvu Forest Reserve. Environmental Conservation Journal. 2023;44(1):98-112. Available:https://doi.org/10.1016/j.envcon.2023.110561
38. Mwalyosi RBB, Burgess ND, Madoffe SS. Forest conservation and carbon sequestration in Tanzania's Eastern Arc Mountains: Current challenges and future prospects. Tropical Conservation Science. 2024;13(1):1–16. Available:https://doi.org/10.1177/19400829240324

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/123170