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*Research Article*

# Environmental and Economic Forecasting of Biomass and Carbon Dynamics under Business-as-Usual, Conservation, and Degradation Scenarios in Mkungunero Game Reserve, Tanzania

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***Abstract -*** *The study conducted on the Mkungunero Game Reserve (MKGR) highlighted the significant role of savanna and dryland ecosystems in the global carbon cycle, particularly in sub-Saharan Africa. It forecasted biomass, carbon, and $CO_2$ dynamics from 2020 to 2050 under three land-management scenarios: Business-as-Usual (BAU), Conservation (COS), and Degradation (DIS). The study utilized a scenario-based land use/land cover framework, integrating spatial projections with biomass parameters and IPCC-compliant carbon accounting. Findings indicated that under the BAU scenario, MKGR would experience substantial biomass loss of approximately 0.53 million Mg, resulting in net carbon emissions of about 0.30 million Mg C and 0.96 million Mg $CO_2$e by 2050. The DIS scenario predicted even greater biomass losses exceeding 0.93 million Mg, with cumulative $CO_2$ emissions nearing 1.60 million Mg $CO_2$e, positioning the reserve as a significant net carbon source. In contrast, the COS scenario forecasted a net biomass recovery of around 0.16 million Mg, leading to net carbon sequestration of approximately 0.07 million Mg C and 0.27 million Mg $CO_2$e. Economic evaluations suggested stark differences, with BAU and DIS pathways incurring cumulative losses of about USD 9.6 million and USD 16.0 million, respectively, while the COS pathway could yield a gross gain of USD USD 2.7 million. The study confirms that natural vegetation significantly influences biomass and carbon stocks, and that management practices are crucial for determining carbon outcomes in MKGR. It highlights the need for conservation, effective monitoring, and climate-finance integration to ensure ecological integrity and economic viability in Tanzania's semi-arid savanna reserves.*

***Keywords -*** *Biomass Depletion, Carbon Emission, Land Use/Cover Change (LULC), Carbon Valuation, Sustainable Game Reserve Management.*

## I. INTRODUCTION

Terrestrial ecosystems are fundamental regulators of the global carbon cycle, functioning both as long-term carbon reservoirs and as dynamic sinks that moderate the rate of atmospheric carbon dioxide ($CO_2$) accumulation. Collectively, vegetation and soils store amounts of organic carbon that are much greater than the anthropogenic emissions per year and hence decisively regulate climate (Pan et al., 2011). Despite the historical domination of tropical forests and climate mitigation discourse, and policy tools, a growing amount of evidence can show that savanna and dryland systems are also playing a key role in carbon dynamics in the region and globally.

Their importance arises not only from localized biomass density but also from their vast spatial extent and the substantial contribution of belowground biomass pools, which are often overlooked in conventional carbon assessments (Grace et al., 2014). Despite this recognition, semi-arid savannas remain systematically underrepresented in long-term carbon forecasting, national greenhouse gas inventories, and climate-finance mechanisms, particularly in sub-Saharan Africa. Such exclusion is associated with both methodological issues, including high spatial heterogeneity, variability due to disturbance, and limited long-term field data and a historical bias towards closed-canopy forest systems. This often limits the visibility of the mitigation potential of the savanna-flavored protected areas in policy discussion and their inclusion in the results-based climate finance. In East Africa, there is a geometrical pace and irreversible change in the savanna ecosystems that are being caused by combination of demographic, environmental, and institutional pressures.

Land-use is changing due to population growth, agricultural development, increased grazing, frequent fire, and infrastructure development, and climate variability and warming additionally contribute to ecosystem pressure (Willcock et al., 2016; IPCC, 2021). Such drivers are expected to increase throughout the next decades, and therefore long-term projections of biomass and carbon pathways are important especially within the period of 2020-2050 in order to conduct evidence-based conservation planning and climate policy development. Static, snapshot-based assessments are increasingly insufficient to capture the cumulative effects of gradual degradation or the potential gains associated with improved management.

Scenario-based approaches have therefore emerged as a powerful analytical framework for exploring plausible ecosystem futures under alternative management pathways. Comparing Business-as-Usual (BAU) trajectories with Conservation (COS) and Degradation (DIS) scenarios, the researchers and policymakers can clearly assess trade-offs and uncertainties, as well as long-term effects of land-use decisions (Griscom et al., 2017). Such approaches are particularly valuable in savanna systems, where ecosystem responses to management interventions are nonlinear and strongly mediated by disturbance regimes and governance effectiveness.

The game reserves incorporated into larger savanna sceneries are particularly priceless, but underestimated, parts of national and regional carbon balances. In contrast to highly safeguarded national parks, most game reserves have a range of human activity and implementations effectiveness, which makes their future utilization as carbon sinks or sources strongly dependent on the management decisions. The Mkungunero Game Reserve (MKGR), which is part of the Tarangire-Manyara region, is a key area of wildlife dispersal and a seasonal home.

At the same time, historical and ongoing anthropogenic pressures including settlement, grazing, cultivation, and fire have raised concerns about progressive biomass depletion and carbon release, particularly under BAU trajectories. Against this backdrop, there remains a notable gap in integrated environmental and economic forecasting of biomass and carbon dynamics in semi-arid game reserves over multi-decadal timeframes. Most of the current literature is either biophysical or economic in the sense that very few research efforts have combined both in a consistent scenario-based context.

Besides, contribution of belowground and deadwood biomass pools which may be a significant portion of overall ecosystem carbon in dryland systems is frequently ignored causing the systematic underestimation of mitigation potential and economic value. The paper attempts to fill these gaps by carrying out an intensive environmental and economic projections of biomass and carbon in 2020–2050 in MKGR under the BAU, COS, and DIS conditions.

This is analyzed based on four hypotheses: $H_1$, that natural vegetation classes accumulate to higher biomass and carbon levels compared to disturbed areas in all situations, $H_2$, that the addition of belowground and deadwood pools of biomass can accumulate to significantly higher levels of total biomass and carbon, $H_3$, that MKGR retains an economically significant quantity of carbon under conservative voluntary carbon market conditions through 2050 and $H_4$, that conservation-oriented pathways stabilize or increase biomass and carbon stock levels in comparison with the BAU and DIS trajectories.

By integrating spatial modelling, IPCC-consistent carbon accounting, uncertainty propagation, and carbon market valuation, the study provides a forward-looking and policy-relevant assessment of MKGR's climate mitigation potential over three decades, with implications for savanna conservation, national carbon accounting, and climate-finance strategies in Tanzania and beyond.

# II. MATERIALS AND METHODS

## *A. Description of the Study Area*

Mkungunero Game Reserve (MKGR) (Figure 1) covers approximately 743 $km^2$ (74,300 ha) and extends across Kondoa District in Dodoma Region and Kiteto District in Manyara Region in central–northern Tanzania. The reserve lies in a semi-arid climatic region typical of the central plateau as well as the northern rift-transition terrains, where climate change has a high control over the productivity of vegetation as well as the biomass accumulation. The rainfall pattern is unimodal as it has a short wet season between January and March with the dry season extending between April and December. Mean annual precipitation varies spatially from approximately 200 mm to 660 mm, while mean annual temperatures typically range between 25 °C and 31 °C, conditions that favor savanna vegetation adapted to seasonal water stress.

The vegetation structure in MKGR is characterised by preponderance of Acacia bushed grasslands, thickets, Acacia flood plain, Acacia flood plain, Pennisetum flood plain, disturbed areas as a result of past and current human activities, such as settlement, cultivation, livestock grazing as well as fire. Both the natural environmental gradients like soil type, topography and hydrology and the anthropogenic influences that have influenced the vegetation composition are reflected in this mosaic across time. Flood-plain systems associated with seasonal drainage lines and depressions support relatively higher woody biomass and productivity, whereas upland bushed grasslands and thickets exhibit strong sensitivity to grazing pressure and fire regimes. Ecologically, MKGR is a part of the Tarangire-Manyara ecosystem that serves as a wet-season dispersal site and dry-season refuge to migratory wildlife moving in and out of the protected landscapes. In combination with a high degree of seasonal variability and known human stressors, these ecological functions render MKGR a model semi-arid savanna system in order to study long-term biomass variations, carbon storage, and carbon sequestration potentials. Consequently, the reserve provides a suitable case study for assessing how alternative management pathways may shape biomass and carbon trajectories over the 2020–2050 period.

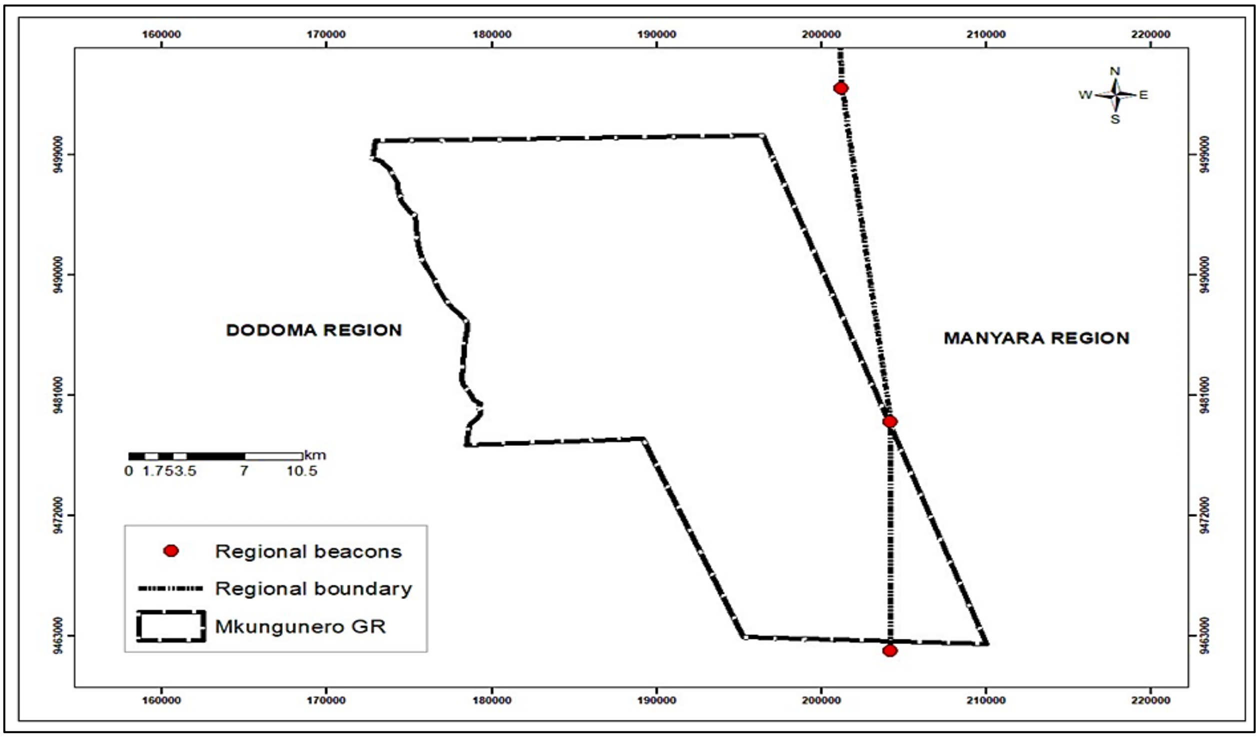


***Figure 1. Location of the Study Area***

## *B. Data Sets*

This study integrated a comprehensive set of spatial, biophysical, socio-economic, and economic datasets to support multi-decadal forecasting (2020–2050) of biomass and carbon dynamics in Mkungunero Game Reserve (MKGR) under Business-as-Usual (BAU), Conservation (COS), and Degradation (DIS) scenarios (Figure 2 and Tables 1-2). The IPCC Tier-1 and Tier-2 good practice also influenced the choice of data, its harmonization and parameterization and was consistent with the national forest and land-use inventory standards of Tanzania, especially the NAFORMA framework. This ensured methodological transparency, internal consistency, and comparability with national greenhouse gas accounting and REDD+ reporting requirements (IPCC, 2006, 2019; NAFORMA, 2015). The primary activity data were a base 2020 land use/land cover (LULC) map of MKGR supervised classification of Sentinel-2 multispectral imagery, which was further enhanced in high resolution where possible.

The accuracy of classification was improved by comparing it with records of management of reserves as well as by field data available in the form of ranger patrols and historic land-use records. To achieve analytical consistency between datasets and situations, more detailed land-cover types were merged into five ecologically significant vegetation-based classes, namely: Acacia bushed grassland, thickets, Acacia flood plain, Pennisetum flood plain, and disturbed areas. These classes represent the dominant structural and functional units governing biomass accumulation and carbon storage within the reserve.

The 2020 LULC map served as the spatial baseline for biomass and carbon estimation and was projected forward to 2030, 2040, and 2050 using scenario-specific transition assumptions. Scenario development combined reserve records, district land-use plans, observed settlement and grazing trends, and evidence from regional land-change studies (Willcock et al., 2016; IPCC, 2021).

Under BAU, observed trends of gradual disturbance expansion and limited enforcement were assumed to continue. The COS scenario included enhanced protection, less anthropogenic pressure and specific regeneration of degraded areas leading to stabilization or restoration of natural vegetation classes. On the other hand, the DIS case took into account rapid degradation caused by the rise in grazing intensity, settlement, fires and progressive replacement of the natural vegetation by the disturbed land. Biomass and carbon parameters were obtained mainly using NAFORMA national forest inventory whereby, the best estimates of woody biomass are available in the country; NAFORMA, which is field-based estimates.

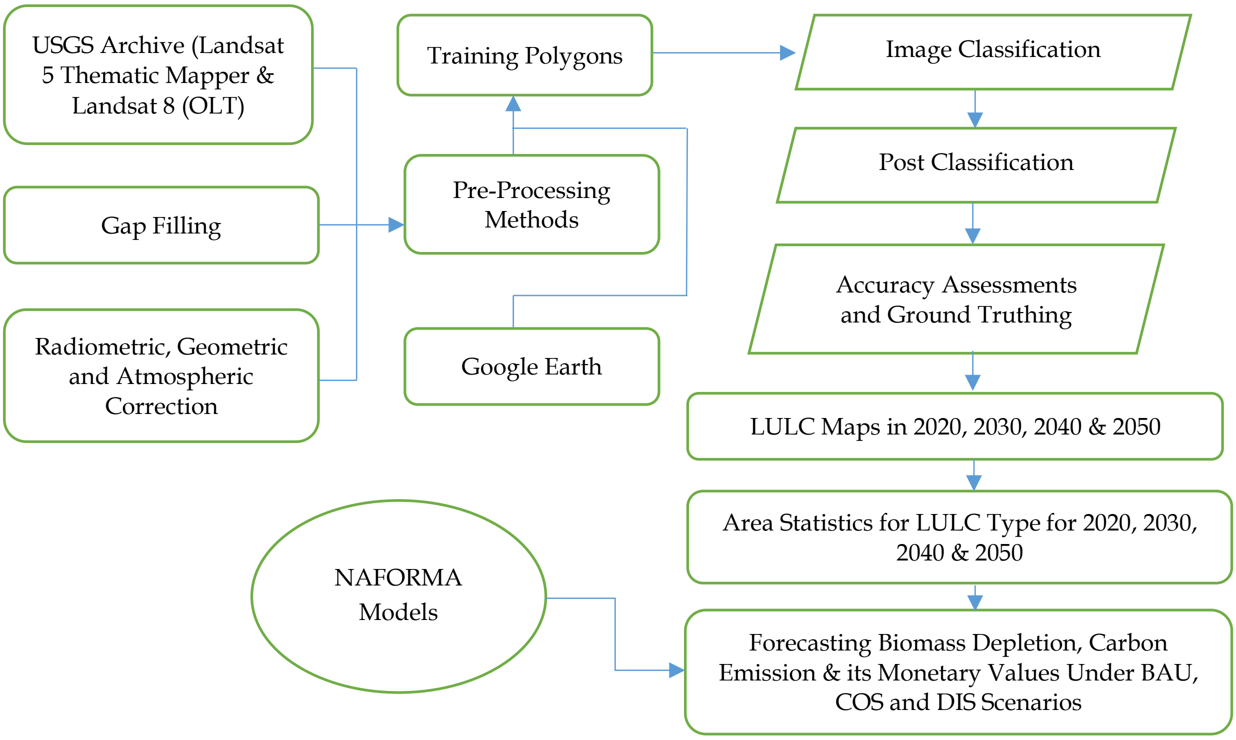


***Figure 2. Flowchart of the Methodological Approach for this Study***

In the case of national inventory classes not being directly related to particular MKGR vegetation unit especially localized flood-plain systems, peer-reviewed estimates of East African savanna and woodland studies were used as a supplement (Munishi and Shear, 2004; Grace et al., 2014; Willcock et al., 2016). Aboveground biomass (AGB) was treated as the core measured pool, while belowground biomass (BGB) and deadwood biomass (DWB) were estimated using IPCC-recommended default ratios (root–shoot ratio = 0.24; deadwood ≈ 10% of AGB). Biomass was converted to carbon using a carbon fraction of 0.47, and carbon was converted to $CO_2$ equivalents using the molecular weight ratio 44/12, consistent with IPCC Good Practice Guidelines (IPCC, 2006, 2019). These parameters were applied uniformly across all scenarios and time steps to ensure comparability of results.

To assess economic implications, projected $CO_2$ stocks under each scenario and time horizon were valued using conservative voluntary carbon market price ranges (USD 3–15 $Mg^{-1}$ $CO_2e$), reflecting recent market syntheses (Hamrick & Gallant, 2017; Ecosystem Marketplace, 2023). The method of price sensitivity made it possible to determine the carbon revenue patterns of 2020 to 2050 without risking overestimating financial gains. Reported values represent gross potential revenues and exclude transaction costs, buffers, leakage, and permanence risks, which are addressed conceptually in the discussion.

**Table 1. LULC Area (ha) and Decadal Plus Cumulative Changes in MKGR under BAU, COS, and DIS Scenarios (2020–2050)**

| LULC Class | 2020 | 2030 | 2040 | 2050 | Δ2020–2030 | Δ2030–2040 | Δ2040–2050 | Δ2020–2050 |
|---|---|---|---|---|---|---|---|---|
| **Business-as-Usual (BAU)** | | | | | | | | |
| ABG | 30,670 | 29,200 | 27,500 | 25,800 | −1,470 | −1,700 | −1,700 | −4,870 |
| TH | 12,935 | 12,100 | 11,200 | 10,300 | −835 | −900 | −900 | −2,635 |
| AFP | 10,988 | 10,400 | 9,700 | 9,000 | −588 | −700 | −700 | −1,988 |
| PFP | 6,613 | 6,300 | 5,900 | 5,500 | −313 | −400 | −400 | −1,113 |
| DIS | 13,095 | 15,300 | 19,000 | 23,700 | +2,205 | +3,700 | +4,700 | +10,605 |
| **Conservation (COS)** | | | | | | | | |
| ABG | 30,670 | 30,900 | 31,200 | 31,500 | +230 | +300 | +300 | +830 |
| TH | 12,935 | 13,200 | 13,500 | 13,800 | +265 | +300 | +300 | +865 |
| AFP | 10,988 | 11,200 | 11,400 | 11,600 | +212 | +200 | +200 | +612 |
| PFP | 6,613 | 6,800 | 7,000 | 7,200 | +187 | +200 | +200 | +587 |
| DIS | 13,095 | 11,900 | 11,200 | 10,200 | −1,195 | −700 | −1,000 | −2,895 |
| **Degradation (DIS)** | | | | | | | | |
| ABG | 30,670 | 28,600 | 25,900 | 23,000 | −2,070 | −2,700 | −2,900 | −7,670 |
| TH | 12,935 | 11,800 | 10,200 | 8,700 | −1,135 | −1,600 | −1,500 | −4,235 |
| AFP | 10,988 | 9,900 | 8,500 | 7,200 | −1,088 | −1,400 | −1,300 | −3,788 |
| PFP | 6,613 | 5,900 | 5,100 | 4,300 | −713 | −800 | −800 | −2,313 |
| DIS | 13,095 | 17,100 | 24,600 | 31,100 | +4,005 | +7,500 | +6,500 | +18,005 |

ABG = Acacia bushed grassland, TH= Thickets, AFP= Acacia flood plain, PFP= Pennisetum flood plain, and DIS= Disturbed areas

**Table 2. Biomass Density Parameters by LULC Class in MKGR**

| LULC Class | Biomass Density ($Mg\ ha^{-1}$) | | | Total |
|---|---|---|---|---|
| | **Aboveground** | **Belowground** | **Deadwood** | |
| Acacia bushed grassland | 35.0 | 8.4 | 3.5 | **46.9** |
| Thickets | 55.0 | 13.2 | 5.5 | **73.7** |
| Acacia flood plain | 70.0 | 16.8 | 7.0 | **93.8** |
| Pennisetum flood plain | 45.0 | 10.8 | 4.5 | **60.3** |
| Disturbed areas | 10.0 | 2.4 | 1.0 | **13.4** |
| **Total** | **215.0** | **51.6** | **21.5** | **288.1** |

# III. RESULTS AND DISCUSSION

## A. Results

### a. Biomass Depletion from Mkungunero Game Reserve for the Period 2020 to 2050

The combined scenario analysis reveals markedly divergent biomass trajectories for Mkungunero Game Reserve (MKGR) over the 2020–2050 period, underscoring the decisive role of management pathways in shaping long-term ecosystem outcomes (Table 3). Under the Business-as-Usual (BAU) scenario, MKGR experiences a net biomass loss of approximately 0.53 million Mg, driven primarily by the contraction of natural vegetation classes and their conversion into disturbed land.

The largest absolute proportion of biomass loss is in acacia bushed grasslands, which have large spatial coverage, and thickets and Acacia flood plains, both of which have high biomass density and high areal loss. Though the disturbed areas record net increase in biomass, the increment is associated with increased land covers with low biomass and compensates less than a third of the biomass lost by the natural vegetation. The BAU trajectory therefore represents a persistent, cumulative depletion pathway, eroding ecosystem productivity and carbon sequestration capacity over time.

In contrast, the Conservation (COS) scenario produces a net biomass gain of approximately 0.16 million Mg by 2050. Gains are concentrated in natural vegetation classes particularly thickets, Acacia flood plains, and Acacia bushed grasslands reflecting reduced disturbance and targeted restoration. The fact that the disturbed areas contract simultaneously supports the efficiency of conservation oriented management to reverse the trends of degradation. Notably, COS biomass gains are spread in aboveground, belowground and deadwood pools which implies recovered structural vegetation as well as longer-term carbon pools. In addition, the Degradation (DIS) scenario is the worst case featuring a huge net loss of biomass at a rate of more than 0.93 million Mg per the study period.

The natural vegetation classes are experiencing massive loss of vegetation with Acacia flood plain; Acacia bushed grasslands showing the greatest losses due to increased grazing, settlement, and fires. The disturbed region at DIS has limited biomass gains that are trivial as compared to the scale of the natural loss in vegetation, which produces a greatly negative net balance. This path suggests that the degradation of ecosystems will increase faster and the long-term carbon storage capacity of the reserve will decrease significantly. Across all scenarios, aboveground biomass changes the most, however belowground and deadwood have a contribution of about 25-30% of total gains or losses, which confirms that omission of non-aboveground biomass pool would be a systematic underestimation of long-term biomass dynamics. Collectively, these results demonstrate that management choices, rather than biophysical constraints alone, will determine whether MKGR functions as a stabilizing biomass reservoir or a source of progressive ecological decline by mid-century.

**Table 3. Biomass Depletion in MKGR from 2020 to 2050**

| LULC class | BAU – Biomass change ($10^3$ Mg) | | | | COS – Biomass change ($10^3$ Mg) | | | | DIS – Biomass change ($10^3$ Mg) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AGB | BGB | DWB | Total | AGB | BGB | DWB | Total | AGB | BGB | DWB | Total |
| ABG | −170.5 | −40.9 | −17.1 | −228.4 | +29.1 | +7.0 | +2.9 | +38.9 | −268.5 | −64.4 | −26.9 | −359.7 |
| TH | −144.9 | −34.8 | −14.5 | −194.2 | +47.6 | +11.4 | +4.8 | +63.8 | −232.9 | −55.9 | −23.3 | −312.1 |
| AFP | −139.2 | −33.4 | −13.9 | −186.5 | +42.8 | +10.3 | +4.3 | +57.4 | −265.2 | −63.6 | −26.5 | −355.3 |
| PFP | −50.1 | −12.0 | −5.0 | −67.1 | +26.4 | +6.3 | +2.6 | +35.4 | −104.1 | −25.0 | −10.4 | −139.5 |
| DIS | +106.1 | +25.5 | +10.6 | +142.1 | −29.0 | −7.0 | −2.9 | −38.8 | +180.1 | +43.2 | +18.0 | +241.3 |
| **Total** | −398.6 | −95.7 | −39.9 | −534.1 | +116.9 | +28.1 | +11.7 | +156.7 | −690.6 | −165.7 | −69.1 | −925.4 |

ABG = Acacia bushed grassland, TH= Thickets, AFP= Acacia flood plain, PFP= Pennisetum flood plain, and DIS= Disturbed areas

### b. Carbon Emission from Mkungunero Game Reserve for the Period 2020 to 2050

The projected biomass transitions between 2020 and 2050 translate into substantial and scenario-dependent carbon emissions or sequestration outcomes for Mkungunero Game Reserve (MKGR) (Table 4). Across scenarios, changes in natural vegetation extent dominate the carbon balance, confirming the central role of savanna vegetation in regulating ecosystem-scale carbon dynamics. Under the Business-as-Usual (BAU) scenario, MKGR suffers a net loss of 0.29 million Mg C of carbon in the study period, which is similar to considerable cumulative carbon emission.

The processes that cause the greatest carbon release on the basis of BAI include contraction of Acacia bushed grasslands, thickets, and Acacia flood plains which contribute over 95% of the total carbon emissions. Whereas the area expansion of disturbed lands leads to the localized carbon benefits, the carbon gains only manifest the extension of low-carbon land covers and compensate less than a quarter of the carbon lost on natural vegetation. This outcome indicates that BAU trajectories progressively weaken the reserve's function as a carbon sink and instead shift it toward a net carbon source.

In contrast, the Conservation (COS) scenario yields a net carbon gain of approximately 0.07–0.08 million Mg C, indicating net carbon sequestration over the 2020–2050 period. The carbon benefits are spread over all the main natural vegetation categories with thickets and flood plains having a relatively high recovery as they have an increased biomass density. Simultaneous decrease in disturbed regions supports the success of conservation and restoration of reduced areas in overturning historical trends of degradation. Notably, sequestration gains are realized not just in the aboveground biomass, but also in the belowground pools as well as the deadwood pools, which increases the permanence of carbon on a long term basis.

The Degradation (DIS) scenario represents the most severe trajectory, with net carbon emissions exceeding 0.43 million Mg C by 2050. The losses occur in all the classes of natural vegetation with the greatest loss in absolute carbon being experienced in Acacia bushed grasslands and flood plains. Whereas disturbed regions grow and store some of the carbon, the returns are simple compared to the scale of the emissions produced by high-carbon vegetation. The DIS pathway therefore implies accelerated conversion of MKGR into a persistent carbon-emitting landscape, with long-term implications for climate mitigation commitments.

Across all scenarios, aboveground carbon accounts for the largest share of emissions and sequestration, but belowground and deadwood pools collectively contribute approximately 30% of total carbon change, confirming that exclusion of non-aboveground pools would result in systematic underestimation of both carbon emissions and sequestration. Overall, the results demonstrate that management choices between 2020 and 2050 will determine whether MKGR remains a net carbon sink or transitions into a sustained carbon source, with profound implications for biodiversity conservation, climate policy, and carbon-finance opportunities.

**Table 4. Carbon Emission from MKGR for the Period 2020 – 2050**

| **LULC Class** | **BAU – Carbon change ($10^3$ Mg C)** | | | | **COS – Carbon change ($10^3$ Mg C)** | | | | **DIS – Carbon change ($10^3$ Mg C)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **AGB** | **BGB** | **DWB** | **Total** | **AGB** | **BGB** | **DWB** | **Total** | **AGB** | **BGB** | **DWB** | **Total** |
| ABG | −80.1 | −19.2 | −8.0 | −107.4 | +13.7 | +3.3 | +1.4 | +18.3 | −126.2 | −30.3 | −12.6 | −169.1 |
| TH | −68.1 | −16.3 | −6.8 | −91.3 | +22.4 | +5.4 | +2.2 | +30.0 | −109.5 | −26.3 | −10.9 | −146.7 |
| AFP | −65.4 | −15.7 | −6.5 | −87.6 | +20.1 | +4.8 | +2.0 | +27.0 | −124.6 | −29.9 | −12.5 | −167.0 |
| PFP | −23.5 | −5.6 | −2.4 | −31.5 | +12.4 | +3.0 | +1.2 | +16.6 | −48.9 | −11.7 | −4.9 | −65.6 |
| DIS | +49.8 | +12.0 | +5.0 | +66.8 | −13.6 | −3.3 | −1.4 | −18.2 | +84.6 | +20.3 | +8.5 | +113.4 |
| **Total** | −187.3 | −89.0 | −18.7 | −295.0 | +55.0 | +13.2 | +5.5 | +73.6 | −324.6 | −77.9 | −32.5 | −434.9 |

ABG = Acacia bushed grassland, TH= Thickets, AFP= Acacia flood plain, PFP= Pennisetum flood plain, and DIS= Disturbed areas

*c. Carbon Dioxide Emission from Mkungunero Game Reserve for the period 2020 to 2050*

Projected biomass dynamics between 2020 and 2050 translate into substantially different $CO_2$ emission trajectories for Mkungunero Game Reserve (MKGR) depending on the management pathway adopted (Table 5). These results highlight the sensitivity of savanna carbon balances to land-use decisions and disturbance regimes over multi-decadal time horizons. In the Business-as-Usual (BAU) scenario, the net source of MKGR is estimated to be 0.92 million Mg $CO_2e$ by 2050. Aboveground biomass losses by themselves generate almost 75% of the total $CO_2$ emissions because of widespread contraction of Acacia dominated vegetation and thickets. That underestimation of the total $CO_2$ emission by omission of non-aboveground factors is approximately 25%, of the total belowground and deadwood capture. Even when the disturbed regions are expanded, the $CO_2$ uptake is not that great, which cannot counter the loss of high-carbon natural vegetation to support a net carbon-emitting course would prove the existence of a net carbon-emitting course under BAU conditions.

In contrast, the Conservation (COS) scenario results in net sequestration of approximately 0.27 million Mg $CO_2$e over the same period. $CO_2$ uptake is distributed across aboveground, belowground, and deadwood pools, indicating structural ecosystem recovery rather than superficial biomass gains. This result proves that enhanced protection and high-priority rehabilitation can make MKGR net carbons sink in three decades, despite the semi-arid climatic limitation. However, Degradation (DIS) case portrays the worst-case scenario where the net $CO_2$ emission levels are more than 1.59 million Mg $CO_2$e by 2050 that is nearly 1.7 times higher than that of BAU. Quick disappearance of the Acacia bushed grasslands, thickets and flood-plain systems encourage extensive aboveground emissions, concurrent dwindling of belowground and deadwood pools decrease long-term retention of carbon. Expansion of disturbed areas provides only marginal $CO_2$ uptake and does not meaningfully mitigate overall emissions.

Across all scenarios, the results clearly demonstrate that management decisions between 2020 and 2050 will determine whether MKGR functions as a net carbon sink or a substantial $CO_2$ source. The magnitude of emissions in BAU and DIS paths and the COS model demonstrate how much of a threat climate change is to the ongoing degradation process, and how much of a contributor game reserves can be to the national mitigation goals, REDD+, strategies, and voluntary carbon markets when ecosystem integrity is maintained.

**Table 5. Carbon Dioxide Emission from MKGR for the Period 2020 – 2050**

| LULC class | BAU – $CO_2$ change ($\times 10^3$ Mg $CO_2$e) | | | | COS – $CO_2$ change ($\times 10^3$ Mg $CO_2$e) | | | | DIS – $CO_2$ change ($\times 10^3$ Mg $CO_2$e) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AGB | BGB | DWB | Total | AGB | BGB | DWB | Total | AGB | BGB | DWB | Total |
| ABG | −293.0 | −70.6 | −29.4 | −393.0 | +50.1 | +12.0 | +5.0 | +67.1 | −462.0 | −111.1 | −46.3 | −619.5 |
| TH | −250.0 | −60.0 | −25.0 | −335.0 | +82.0 | +19.7 | +8.2 | +109.9 | −401.8 | −96.4 | −40.2 | −538.4 |
| AFP | −240.0 | −57.6 | −24.0 | −321.6 | +73.9 | +17.7 | +7.4 | +99.0 | −457.4 | −109.8 | −45.8 | −613.0 |
| PFP | −86.4 | −20.7 | −8.6 | −115.7 | +45.6 | +10.9 | +4.6 | +61.1 | −179.5 | −43.1 | −18.0 | −240.6 |
| DIS | +182.8 | +43.8 | +18.3 | +244.9 | −49.9 | −12.0 | −5.0 | −66.9 | +310.6 | +74.5 | +31.1 | +416.1 |
| **Total** | −686.5 | −164.9 | −105.3 | −956.7 | +201.7 | +48.3 | +20.2 | +270.2 | −1,190.1 | −286.9 | −119.2 | −1,596.2 |

ABG = Acacia bushed grassland, TH= Thickets, AFP= Acacia flood plain, PFP= Pennisetum flood plain, and DIS= Disturbed areas

*d. Economic Loss of Mkungunero Game Reserve for the Period 2020 to 2050*

Projected carbon dioxide dynamics translate into substantial and strongly scenario-dependent economic outcomes for Mkungunero Game Reserve (MKGR) when evaluated under conservative voluntary carbon market conditions (Table 6). The calculated values of carbon trade indicate the financial implications of the land-use and management options between the 2020–2050 period. In the Business-as-Usual (BAU) scenario, the net economic loss that MKGR will suffer by 2050 is a loss of foregone carbon revenue worth USD 9.6 million (≈ 96 lakhs). The carbon emission of Acacia bushed grasslands, thickets, and Acacia flood plains constitutes the driving force of losses and more than 80% of the total economic loss. Even though disturbed areas have low biomass, the gains are offset by less than a quarter of the losses of natural vegetation even though expansion adds only limited carbon value. The BAU trajectory therefore reflects a gradual but persistent erosion of the reserve's carbon-finance potential.

In contrast, the Conservation (COS) scenario yields a net economic gain of approximately USD 2.7 million (≈ 27 lakhs) over the same period. The generated carbon revenues in all vegetation classes and thickets and flood plains are disproportionately contributing to the carbon revenues since the carbon densities in the former are higher. The net value is further increased by the contraction of disturbed areas which indicates that conservation-oriented management does not only stabilize ecological integrity, but also generates quantifiable economic positive qualities of mitigating climate services. Besides, the Degradation (DIS) scenario represents the most economically damaging pathway, with net losses approaching USD 16.0 million (≈ 160 lakhs) by 2050 nearly 1.7 times greater than BAU losses. The high carbon vegetation is accelerated in degradation, which is over and above the small carbon accrual of the disturbed area expansion leading to extreme financial risk in the long term. This situation shows that the unregulated degradation of the land transforms MKGR into an persistent source of economic loss.

Thus, the results demonstrate that carbon-market are closely associated with the ecological patterns. Conservation pathways conserve and increase both biophysical carbon stores and economic worth whereas BAU and DIS trajectories introduce a mounting opportunity cost on the reserve management and national climate-finance aspirations. These results further highlight the need to incorporate carbon economics into the planning of the protected areas especially in semi-arid savanna reserves where management decisions strongly determine long-term environmental and financial outcomes.

**Table 6. Carbon Trade Value (lakhs USD) in MKGR from 2020 to 2050**

| LULC class | BAU – Carbon trade value (lakhs USD) | | | | COS – Carbon trade value (lakhs USD) | | | | DIS – Carbon trade value (lakhs USD) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AGB | BGB | DWB | Total | AGB | BGB | DWB | Total | AGB | BGB | DWB | Total |
| ABG | −29.3 | −7.1 | −2.9 | −39.3 | +5.0 | +1.2 | +0.5 | +6.7 | −46.2 | −11.1 | −4.6 | −61.9 |
| TH | −25.0 | −6.0 | −2.5 | −33.5 | +8.2 | +2.0 | +0.8 | +11.0 | −40.2 | −9.6 | −4.0 | −53.8 |
| AFP | −24.0 | −5.8 | −2.4 | −32.2 | +7.4 | +1.8 | +0.7 | +9.9 | −45.7 | −11.0 | −4.6 | −61.3 |
| PFP | −8.6 | −2.1 | −0.9 | −11.6 | +4.6 | +1.1 | +0.5 | +6.1 | −18.0 | −4.3 | −1.8 | −24.1 |
| DIS | +18.3 | +4.4 | +1.8 | +24.5 | −5.0 | −1.2 | −0.5 | −6.7 | +31.1 | +7.5 | +3.1 | +41.6 |
| **Total** | −68.7 | −16.5 | −10.5 | −95.7 | +20.2 | +4.8 | +2.0 | +27.0 | −119.0 | −28.7 | −11.9 | −159.6 |

ABG = Acacia bushed grassland, TH= Thickets, AFP= Acacia flood plain, PFP= Pennisetum flood plain, and DIS= Disturbed areas

***B. Discussion***

*a. Biomass Depletion from Mkungunero Game Reserve (2020–2050)*

The multi-decadal projections for MKGR reveal clear, management-dependent trajectories of biomass change. Under Business-as-Usual (BAU) the reserve is projected to lose roughly 534,000 Mg of total biomass between 2020 and 2050, while an intensified Degradation (DIS) pathway produces losses on the order of 925,000 Mg, and a Conservation (COS) pathway yields a net gain of ∼157,000 Mg. These magnitudes reflect two interacting processes: (a) area effects (the extensive spatial dominance of Acacia bushed grasslands) and (b) density effects (higher per-hectare biomass in thickets and flood-plain woodlands). The trend of big absolute losses of spatially dominant but moderate-density grasslands and relative proportionate losses of denser thickets and flood plains is similar to the results of regional studies which underscore the combined significance of extent and structure in the dynamics of savanna biomass (Grace et al., 2014; Willcock et al., 2016).

Our results support Hypothesis H1: natural vegetation classes store substantially more biomass than disturbed areas and therefore account for the majority of biomass loss under BAU and DIS. Quantitatively, Acacia bushed grasslands, thickets and flood plains contribute together to the majority of the depletion, although disturbed areas, though growing, are low-biomass states whose area only compensates a minor portion of the losses of intact vegetation. This accords with field and remote-sensing studies in East African drylands showing that land-use conversion to low-biomass uses (cultivation, heavy grazing, settlement) produces persistent biomass deficits and slow recovery trajectories (Ryan, Williams, & Grace, 2011; Munishi & Shear, 2004).

The BAU and DIS projected depletion is also cause of concern ecologically since losses are clustered in structurally complex and hydrologically active units (thickets and flood plains) that contribute disproportionately to ecological services (habitat, forage and soil stabilization) and are slow to regenerate. From a management perspective, the COS scenario shows that degradation trends in the landscape level can be reversed through targeted protection and restoration; the modeled increase in biomass of about ∼157,000 Mg shows that realistic recovery is possible in case disturbance is controlled and the restoration process is maintained over decades. These findings emphasize that land-use policy and enforcement, rather than biophysical constraints alone, will largely determine MKGR's biomass trajectory to 2050.

*b. Carbon Emission from Mkungunero Game Reserve (2020–2050)*

Converting biomass changes to carbon (using the IPCC carbon fraction of 0.47) produces scenario outcomes with direct implications for greenhouse-gas inventories and mitigation planning. The BAU trajectory corresponds to a net carbon loss of ~295,000 Mg C, DIS to ~435,000 Mg C emitted, while COS yields a net sequestration of ~73,600 Mg C across the 30-year horizon. Their values are of comparable magnitude (order of magnitude) to the carbon changes reported in savanna and woodland landscapes in other parts of East Africa under the same projections over time in multi-decadal time frames (Willcock et al., 2016; Munishi and Shear, 2004), and this confirms the argument that savanna protected areas have the capacity to be large reservoirs of terrestrial carbon.

The partitioning of carbon losses across pools is instructive: aboveground pools account for the largest share of carbon change, but belowground and deadwood pools together account for roughly 25–30% of total carbon change. This finding is independent of the empirical literature (Grace et al., 2014; Ryan et al., 2011) and supports Hypothesis H2 excluding belowground and necromass necromass constituents to carbon emissions would underestimate degradation carbon emissions and overestimate the sequestration in a restoration setting. In practice, the findings suggest that to eliminate systematic bias in the valuation of the carbon benefits of preserving savanna, BGB and DWB are needed in national inventories and project MRV.

Methodologically, the absolute carbon estimates depend on the chosen biomass densities and pool-partitioning rules (NAFORMA-informed AGB values, IPCC default R:S and DWB fractions). While this hybrid Tier-2/Tier-1 model is justifiable and is in line with national practice, our findings also support the fact that local allometry is more prone to divergence with national averages especially in flood-plain systems because of local variation in parameters (Chave et al., 2014). Reducing uncertainty will be essential where MKGR seeks to participate in high-integrity carbon finance mechanisms.

*c. Carbon Dioxide Emission from Mkungunero Game Reserve (2020–2050)*

Expressed as $CO_2$ equivalents (using the 44/12 conversion), the modeled outcomes have direct climate-policy salience. BAU implies cumulative net emissions of ~0.96 million Mg $CO_2e$ to 2050, DIS nearly 1.60 million Mg $CO_2e$, whereas COS yields net sequestration of ~0.27 million Mg $CO_2e$. These magnitudes place MKGR within the class of semi-arid protected areas whose management decisions can exert measurable influence on national emissions pathways over multi-decadal timescales. Our findings agree on a larger synthesis that savannas have a cumulative material contribution to the overall carbon balances in the region and that the trajectories of savannas can both enhance and decrease nationwide emission characteristics (Pan et al., 2011; Willcock et al., 2016). The contrast between COS and DIS underlines an important asymmetry where avoiding loss (avoiding loss) is usually cheaper and more doable than recovery of similar stores of carbon once lost (Griscom et al., 2017). Climate-finance perspective shows that from a climate-finance perspective the CO2 amount illustrates that MKGR will be able to offer verifiable mitigation according to a conservation pathway and that failure to cease degradation will create liabilities of persistent emissions.

However, realizing COS-scale sequestration depends on governance, long-term financing, community engagement, and robust MRV frameworks to ensure permanence and additionality; the literature on REDD+ and voluntary carbon markets repeatedly emphasizes these institutional constraints (Chazdon et al., 2020; Hamrick & Gallant, 2017). Consideration of uncertainty is also relevant. Our forecasts are based on defensible central values of biomass densities and pool ratios, however, the probable ±2030% error range (IPCC Tier-1/2 guidance) has broad revenue and emission envelopes. Tier-2, field-calibrated approach would eliminate such bands and make the argument of believable carbon project development.

*d. Economic Loss of Mkungunero Game Reserve (2020–2050)*

Valuing $CO_2$ outcomes at a conservative market price (USD 10 $Mg^{-1}$ $CO_2e$, mid-range for voluntary transactions), we estimate gross carbon trade impacts of roughly –USD 9.6 million (BAU loss), +USD 2.7 million

(COS gain), and –USD 16.0 million (DIS loss) over 2020–2050. Expressed in the lakhs convention used in the region, these correspond to ≈ −95.7, +27.0 and −159.6 lakhs USD respectively. These findings depict the amount of real economic benefits that management decisions have in their real manifestations: conservation activities can result in recoverable revenue streams and yield co-benefits to local communities, but degradation yields foregone revenue and climate liabilities.

Comparatively, the scale of potential revenue and loss is consistent with findings from other savanna projects and REDD+/VCM case studies, in which avoided conversion and restoration can generate significant revenues when summed over the project lifetime and when transaction costs, buffers and permanence provisions are controlled (Griscom et al., 2017; Hamrick and Gallant, 2017).

There are however two significant caveats. And, to start with, the values here are gross potential, net project revenues would be less after considering design, validation, MRV, transaction costs and benefits sharing costs, and after considering buffer pools on non-permanence and leakage adjustments. Second, carbon markets are unstable and sensitive to changes in price; the application of a price range (USD 3–15 $Mg^{-1}$ $CO_2e$) generates significantly different financial effects, and the financial business cases should remain conservative to find project finance (Ecosystem Marketplace, 2023).

These findings partially validate Hypothesis H3: MKGR can retain economically meaningful carbon value under conservative market assumptions if conservation and restoration are implemented (COS). Under BAU, the reserve continues to display some value on paper of the carbon but the aggregate emissions and poor governance diminish the prospects of the bankable revenue.

Our results support conceptually hypothesis H4 that better data (as in Tier-2 calibration) and governance can reduce uncertainty and enhance the practicality of stock reduction into marketable credits is supported conceptually by our results: reducing uncertainty narrows revenue confidence intervals, improves valuation, and strengthens claims of additionality and permanence, all of which are prerequisites for successful carbon finance.

*e. Synthesis, Implications and Research Needs*

Collectively, the results show that MKGR sits at the intersection of ecological importance and climate-finance opportunity. The management decisions of the reserve in 2020-2050 will depend on the options of the reserve: conservation indicates available sequestration and value potential; BAU entails moderate losses; DIS brings a huge rate of emissions and financial expenditures. These results are similar to others in the region that savanna management can constitute sinks or sources of these biomes at policy-relevant scales (Pan et al., 2011; Grace et al., 2014; Willcock et al., 2016).

Policy implications are threefold. First, with, the most effective way to incorporate MKGR into national carbon accounting (including the REDD+ preparation procedures) would enhance the completeness of inventories and establish avenues of results-based finance (URT, 2018; Zahabu et al., 2022). Second, low-cost, high-impact protection (boundary enforcement, community co-management, grazing management, fire control) ought to be prioritized which can avoid high emissions at a lower cost than that of post-degradation restoration. Third, investments in Tier-2 field calibration and an MRV system are essential to reduce uncertainty, increase market credibility, and mobilize finance.

Limitations of this study include reliance on synthesized NAFORMA and literature-derived coefficients (albeit conservative and well-justified) and scenario assumptions that, while grounded in local records and regional studies, cannot capture all socio-political contingencies. Future research ought to focus on field calibration of allometric relationships in MKGR flood-plain and thicket systems, should come up with leakage as well as additionality analysis, and formulate numeric socio-economic feedbacks that can modify the pathways to land-use. In this way, the risks associated with MKGR biomass and carbon futures are manageable: by conserving the reserve on time and ensuring a strict MRV, the reserve will be able to preserve or even grow its climatic and economic value; otherwise, the reserve will most likely become a significant source of $CO_2$ emissions and the resulting economic loss by mid-century.

# IV. CONCLUSION AND RECOMMENDATIONS

### *A. Conclusion*

This study provides a comprehensive, scenario-based assessment of biomass dynamics, carbon emissions, carbon dioxide ($CO_2$) fluxes, and associated economic implications in Mkungunero Game Reserve (MKGR) over the period 2020–2050. By integrating land use/land cover (LULC) projections, nationally consistent biomass parameters, IPCC-compliant carbon accounting, and conservative carbon market valuation, the analysis offers a robust evidence base for understanding how alternative management pathways shape both environmental and economic outcomes in a semi-arid savanna reserve. The findings also prove that the carbon balance of MKGR in the future is very sensitive to the management decisions. The business-as-usual (BAU) scenario indicates that the reserve will undergo a long-term shrinkage of biomass, which will result in net carbon and $CO_2$ emission and loss of mitigation potential of climate. These trends are intensified by the Degradation (DIS) scenario, leading to serious losses of natural vegetation, massive cumulative $CO_2$ emissions, and lost value of foregone economic value. In contrast, the Conservation (COS) scenario reverses degradation trajectories, yielding net biomass recovery, carbon sequestration, and positive carbon trade value by mid-century. These findings confirm that conservation-oriented management can transform MKGR from a net carbon source into a net carbon sink within three decades, even under semi-arid climatic conditions.

Critically, the study shows that belowground and deadwood biomass pools contribute a substantial share (approximately 25–30%) of total biomass and carbon change, validating the importance of comprehensive carbon accounting frameworks. The omission of these pools would dramatically overstate the amount of emission in BAU as well as in the DIS, and sequestration in COS, and this has direct consequences on the national greenhouse gas inventories as well as their eligibility in the carbon markets. The results of the scenario also indicate that the spatial area of the vegetation classes is as predictive as the per-hectare biomass densities of the carbon effects at the landscape scale, highlighting the vulnerability of widespread Acacia-dominated systems to incremental degradation.

From an economic perspective, the valuation of $CO_2$ dynamics under conservative voluntary carbon market assumptions reveals that carbon finance outcomes mirror ecological trajectories. The conservation pathways have high economic value in the long term, whereas BAU and DIS pathways have increasing opportunity costs and climate liabilities. Despite the fact that the estimated values are gross potential revenues, and are not able to capture the cost of transactions, buffers and market volatility, it is evident that inaction can be associated with a real cost, and proactive management can be able to access the climate-finance opportunities in accordance with biodiversity conservation.

Overall, the study fills an important knowledge gap by providing a long-term, integrated environmental–economic forecast for a semi-arid game reserve in East Africa. It underscores the importance of the fact that savanna-based protected areas which are commonly neglected as an element of mitigation strategies can contribute to the national and regional climate targets in a measurable manner in the event that they are managed appropriately. The findings therefore have direct relevance for conservation planning, climate policy, REDD+ readiness, and voluntary carbon market engagement in Tanzania and comparable savanna landscapes.

### *B. Recommendations*

Based on the empirical findings and their policy and management implications, this study advances a set of interlinked recommendations aimed at safeguarding the ecological integrity of Mkungunero Game Reserve (MKGR) while enhancing its contribution to national climate mitigation and sustainable financing objectives. First, there is a clear need to strengthen protection and enforcement within MKGR. To reduce the further spread of disturbed areas, better boundary delineation, increase in the capacity of the rangers, and proper management of grazing, settlement as well as fire are needed.

As illustrated in the scenario analysis, quick and high-impact intervention is quite cheaper than trying to undo degradation when it has become internal. Elimination of additional loss of biomass along Business-as-Usual pathways and Degradation pathways would prevent massive cumulative carbon emissions and associated economic losses over the 2020-2050 period. Second, integrating MKGR into national carbon accounting and climate policy frameworks is critical. Explicit inclusion of game reserves and savanna ecosystems in Tanzania's greenhouse gas inventories, REDD+ architecture, and long-term low-emission development strategies would improve the completeness and accuracy of national reporting. Considering the large amounts of carbon stocks and flux found in this research, the exclusion of such systems can easily lead to systematic underestimation of emissions as well as mitigation potential at the national level. Third, the results highlight the value of setting conservation and restoration pathways as a key management agenda. Specific restorative measures on degraded areas, with the rigorous protection of the high-biomass areas like thickets and flood plains, can produce a great deal of biomass recovery and net carbon sequestration. The Conservation scenario illustrates that sustained management interventions can stabilize and even enhance carbon stocks over multi-decadal horizons, thereby transforming MKGR into a net carbon sink despite its semi-arid context.

Fourth, the study highlights the necessity of developing a Tier-2 monitoring, reporting, and verification (MRV) framework. Field-based measurements of biomass, local calibration of allometric equations and both belowground and deadwood pool monitoring would represent a significant reduction in uncertainty in biomass and carbon estimates. An effective Tier-2 MRV system would facilitate not only scientific accuracy, but also increase the credibility of carbon markets, which is a precondition of using high- integrity climate finance mechanisms. Fifth, it is highly reasonable to use carbon finance to finance the management of reserves and local livelihoods. Carbon finance under REDD +, jurisdictional schemes or voluntary carbon market needs to be sought as an additional stream of funding and not as a solution in its own right. Proper benefit-sharing schemes with the neighboring communities can enhance the conservation support of the local people, decrease stress on the reserve resources, and enhance the permanence of carbon benefits, hence coordinating the ecological goals with the socio-economic development.

Sixth, uncertainty and price sensitivity should be explicitly incorporated into management and investment decision-making. Considering the fundamental differences in the amount of biomass estimated and the volatility in the price of carbon, it is necessary that assumptions are conservative and that management structures are adaptive. Plans that include uncertainty ranges by scenario planning have the potential to reduce financial risk and have policy and investment decisions that can survive the changing ecological and market conditions. Finally, the research proposes future research on the ongoing studies about savanna carbon processes to be expanded. The future efforts should focus on long-term field calibration of biomass pools, better climate-vegetation interactions modelling, and further study of socio-economic factors of land-use change. Strengthening the empirical foundation of savanna carbon science will enhance the reliability of projections and inform more effective, context-sensitive mitigation strategies. Thereof, Mkungunero Game Reserve represents both a climate risk and a climate opportunity. The trajectory it follows toward 2050 will be shaped largely by policy choices and management effectiveness implemented in the present. By prioritizing conservation, strengthening governance structures, and investing in robust carbon accounting and monitoring systems, MKGR can safeguard its ecological integrity while making a meaningful contribution to climate mitigation and sustainable financing goals in Tanzania and beyond.

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