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Original Research

FORECASTING NATURE'S CONTRIBUTIONS TO PEOPLE IN KAZIMZUMBWI FOREST RESERVE, TANZANIA: AN INVEST-BASED LULC AND BENEFIT TRANSFER VALUATION

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Abstract
Land use and land cover (LULC) changes significantly impacted ecosystem degradation in peri-urban forest reserves, particularly in rapidly urbanising sub-Saharan Africa, with Tanzania exemplifying this trend. The Kazimzumbwi Forest Reserve (KFR) faced increasing pressures from urban expansion, infrastructure development, and competing land-use priorities. This study forecasted future LULC trajectories and their economic and functional implications for the period 2024–2054, guided by four hypotheses concerning changes in ecosystem services across alternative land-use scenarios. The study employed scenario-based LULC forecasting combined with ecosystem service valuation, using historical LULC data to construct Markov transition probability matrices and spatial allocation models. Three scenarios were simulated: Business-as-Usual (BAU), Conservation-Oriented Scenario (COS), and Development-Intensive Scenario (DIS). Ecosystem service values (ESV) were estimated using established valuation coefficients, enabling a comprehensive assessment of projected ecosystem outcomes. The results indicated pronounced scenario-dependent differences. Under the BAU scenario, total ESV declined modestly by 2.7% at the local scale and 3.0% at the global scale, primarily due to losses in high-value forest-based ecosystem services, despite limited gains from lower-value secondary vegetation. In contrast, the COS generated net gains in ecosystem services (+5.2% locally and +5.4% globally) through enhanced forest persistence and recovery of key regulating and supporting functions. The DIS resulted in severe ecosystem degradation, with total ESV declining by more than 20% and critical forest functions collapsing, while increases in shrubland and grassland failed to compensate for these losses. The study's findings supported all four hypotheses, highlighting the sensitivity of ecosystem service outcomes to land-use governance. Conservation-oriented pathways prevented ecosystem loss and enhanced functions, while development-intensive pathways led to ecological and economic costs. Recommendations included prioritizing conservation planning, forest restoration, ecosystem service valuation, and community-based livelihoods for sustainability.

Keywords: Land use and Land Cover Change; Ecosystem Service Valuation; Scenario-based Modelling; Peri-urban Forest Reserves; Tanzania

Introduction

Ecosystems constitute a fundamental foundation for human well-being by generating a diverse array of material, regulating, and non-material benefits that sustain livelihoods, economic activity, and ecological stability. These benefits are commonly conceptualized as ecosystem services or, within the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) framework, as Nature's Contributions to People (NCP), encompassing provisioning services such as timber and non-timber forest products, regulating services including climate regulation and water purification, and cultural contributions that support recreation, social identity, and spiritual values (Jai et al., 2019; Díaz et al., 2019). Forest ecosystems are particularly critical in the Global South, where a large proportion of rural and peri-urban populations depend directly on forest resources for income, food security, energy, and climate resilience (FAO, 2022; Levers et al., 2018). Beyond local livelihoods, forests provide global public goods through carbon sequestration, biodiversity conservation, and regulation of hydrological and climatic systems.

Despite their recognized importance, forest ecosystems are increasingly threatened by accelerating land-use and land-cover (LULC) change driven by agricultural expansion, urbanization, infrastructure development, and demographic pressure. Empirical evidence consistently identifies LULC change as the primary driver of ecosystem service degradation in sub-Saharan Africa, contributing to declining carbon stocks, disrupted hydrological processes, habitat fragmentation, and biodiversity loss (Song et al., 2018; Tasi et al., 2025). Tanzania exemplifies these trends, where rapid population growth and spatial expansion of urban centers particularly around Dar es Salaam have intensified pressure on protected forest reserves and surrounding landscapes (Ract et al., 2024; Daniele, 2024). These pressures are especially pronounced in peri-urban forest systems, which experience competing demands for conservation, settlement, agriculture, and infrastructure development.

Kazimzumbwi Forest Reserve, located within Tanzania's rapidly urbanizing coastal zone, represents an ecologically significant yet increasingly vulnerable forest ecosystem. The reserve provides a wide range of ecosystem services, including carbon sequestration, local climate regulation, groundwater recharge, biodiversity habitat, and livelihood support for adjacent communities. However, empirical studies indicate that forest reserves in Tanzania's coastal belt are experiencing accelerated encroachment, forest degradation, and land conversion, undermining their long-term capacity to sustain ecosystem service flows (Ntukey et al., 2022; Burgess et al., 2017). While previous research has documented historical land-cover change in parts of the coastal region, there remains a critical lack of forward-looking, scenario-based assessments that quantify how ecosystem service values are likely to evolve under continued land-use dynamics. This knowledge gap limits the ability of planners and policymakers to anticipate future trade-offs between development and ecosystem sustainability.

Although ecosystem service valuation has gained increasing prominence in environmental research and policy, much of the existing work in Tanzania remains static and retrospective, emphasizing historical patterns of land-cover change without projecting future implications for ecosystem service provision and value. Such approaches constrain the capacity of land-use planners and decision-makers to evaluate long-term ecological and socio-economic consequences of current development pathways. Moreover, relatively few valuation studies explicitly align with globally recognized frameworks such as IPBES and The Economics of Ecosystems and Biodiversity (TEEB), thereby limiting policy relevance, comparability, and

integration into national planning and accounting systems (Polasky et al., 2015; Normyle et al., 2023). In the specific context of Kazimzumbwi Forest Reserve, there is insufficient empirical evidence on how projected LULC changes will influence both the magnitude and composition of ecosystem service values over extended time horizons.

In response to these gaps, this study aims to forecast ecosystem service values conceptualized as Nature's Contributions to People in Kazimzumbwi Forest Reserve over the period 2024–2054, using an IPBES and TEEB-aligned valuation framework. By integrating historical LULC analysis, spatially explicit InVEST modeling, and LULC-driven benefit transfer valuation, the study quantifies current ecosystem service values and projects their evolution under alternative land-use scenarios. This forward-looking approach enables an assessment of how different development trajectories may alter the capacity of the forest reserve to generate ecosystem benefits over the next three decades and provides a basis for evaluating long-term sustainability outcomes.

The study is guided by two core research objectives: (i) to forecast changes in the economic values of ecosystem services resulting from land-use and land-cover change (LULCC) in Kazimzumbwi Forest Reserve from 2024 to 2054, and (ii) to analyze changes in forecasted economic values of ecosystem functions across different LULC types over the same period. From two objectives four hypotheseses tested: (i) H_{1a}: Under the Business-as-Usual and Development-intensive scenarios, total ecosystem service values will decline significantly between 2024 and 2054; (ii) H_{1b}: Under the Conservation-oriented scenario, ecosystem service values will be maintained or increase over the same period; (iii) H_{2a}: Regulating ecosystem functions (e.g., climate regulation and water regulation) will experience greater economic value losses under non-forest LULC expansion than provisioning functions; and (iv) H_{2b}: LULC types characterized by higher vegetation cover will show greater resilience in ecosystem service values across all scenarios. Addressing these hypotheses contributes to a more anticipatory and evidence-based understanding of forest–development interactions in peri-urban contexts.

The significance of this study lies in its scientific, methodological, and policy contributions. Scientifically, it advances ecosystem service research in sub-Saharan Africa by moving beyond retrospective assessments toward long-term, scenario-based forecasting of ecosystem service values using spatially explicit modeling. Methodologically, the integration of InVEST modeling with benefit transfer valuation within an IPBES-consistent framework responds to growing calls for harmonized, decision-relevant ecosystem assessments. From a policy perspective, the findings provide quantitative evidence to support land-use planning, forest conservation strategies, climate mitigation efforts, and sustainable development decision-making. By translating projected ecological change into economic and social values, the study enhances the visibility of forest ecosystems in policy discourse and supports the operationalization of natural capital accounting initiatives, including the System of Environmental-Economic Accounting–Ecosystem Accounting (SEEA-EA), within the Tanzanian context.

Motivation of the Study

The motivation for this study arises from the growing recognition that sustainable development cannot be achieved without explicitly accounting for the value of nature in economic and planning decisions. Global assessments consistently demonstrate that the degradation of ecosystem services poses systemic risks to food security, climate resilience, and economic stability, particularly in developing countries (Jai et al., 2019; Sivadas, 2022). Yet, empirical

valuation evidence remains underutilized in land-use decision-making due to methodological gaps, data limitations, and the absence of long-term projections.

At the national level, Tanzania's development trajectory characterized by rapid urban expansion and infrastructure investment has intensified competition for land resources, often at the expense of forest ecosystems. This study is motivated by the need to provide empirically grounded, future-oriented evidence that can inform more balanced development pathways. By forecasting ecosystem service values rather than merely documenting past losses, the study aligns with contemporary calls for anticipatory governance and scenario-based environmental planning (Bourgault et al., 2020; Kothawala et al., 2021). Ultimately, the study seeks to bridge the persistent gap between ecosystem science and policy implementation by producing decision-relevant knowledge grounded in robust spatial and economic analysis.

Theoretical Framework

This study is grounded in an integrated theoretical framework drawing on Ecosystem Services Theory, Nature's Contributions to People (IPBES framework), and Natural Capital Theory, operationalized through spatial modeling and economic valuation.

Ecosystem Services Theory posits that ecosystems generate flows of benefits that directly and indirectly support human well-being and economic systems. This perspective emphasizes the functional linkages between biophysical processes and societal outcomes, providing a basis for identifying, quantifying, and valuing ecosystem services (Costanza et al., 2017; Roy & Bachelier, 2020). Building on this foundation, the IPBES framework reframes ecosystem services as Nature's Contributions to People, explicitly recognizing cultural, relational, and context-specific values alongside material benefits (Díaz et al., 2019). This broader conceptualization is particularly relevant in African contexts, where forest values extend beyond market-based benefits to include social identity, traditional practices, and local climate regulation.

Natural Capital Theory further underpins the study by conceptualizing ecosystems as capital assets that generate flows of services over time. From this perspective, land-use change represents a transformation or depletion of natural capital stocks, with long-term implications for sustainable development (Dasgupta, 2021). The integration of this theory with spatially explicit tools such as InVEST allows for the empirical assessment of how changes in land cover affect ecosystem service supply and economic value under alternative future scenarios (Sharp et al., 2020; Prairie et al., 2021).

Together, these theoretical perspectives provide a coherent framework for linking land-use dynamics, ecosystem processes, and human well-being. By embedding valuation within this integrated framework, the study ensures conceptual consistency with IPBES and TEEB principles while generating empirically robust evidence capable of informing land-use planning, conservation policy, and sustainable development strategies.

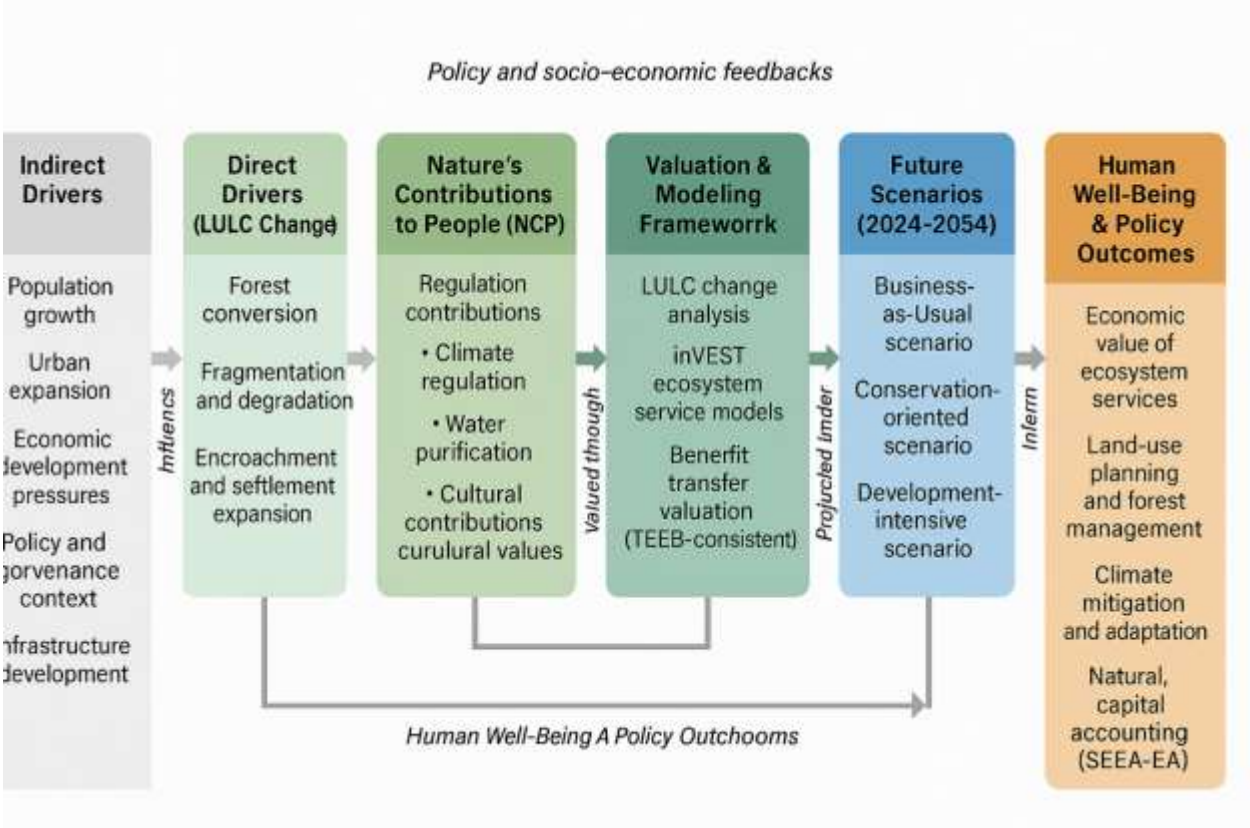

Figure 1: Conceptual framework

Materials and Methods

Study Area

This study was conducted in Kazimzumbwi Forest Reserve, located in the coastal zone of Tanzania within the peri-urban hinterland of Dar es Salaam, one of the fastest-growing metropolitan regions in sub-Saharan Africa. The reserve lies within the Eastern African Coastal Forests ecoregion, a globally recognized biodiversity hotspot characterized by high levels of endemism and ecological significance (Burgess et al., 2017). Kazimzumbwi Forest Reserve covers approximately 1,200 hectares and is dominated by coastal forest vegetation interspersed with secondary regrowth, woodland patches, and degraded areas resulting from anthropogenic pressure. The climate is tropical sub-humid, with bimodal rainfall patterns and mean annual precipitation ranging between 900 and 1,200 mm, conditions that support diverse forest ecosystem functions including biomass production, carbon sequestration, and groundwater recharge.

The reserve plays a critical role in supporting local and regional ecosystem services, including climate regulation, water infiltration, biodiversity habitat provision, and livelihood resources for surrounding communities. However, its proximity to Dar es Salaam exposes it to intense land-use pressure from urban expansion, informal settlements, charcoal production, and agricultural encroachment. Empirical studies show that peri-urban forest reserves in Tanzania experience disproportionately high rates of land-cover change compared to remote protected areas, leading to rapid ecosystem degradation and declining service provision (Ntukey et al.,

2022; Burgess et al., 2017). These characteristics make Kazimzumbwi Forest Reserve a suitable and policy-relevant case study for assessing long-term ecosystem service dynamics under alternative land-use trajectories.

Data Sets and Methods

This study employed an integrated, mixed-methods spatial modeling framework to achieve two interrelated objectives: (i) to forecast changes in the economic values of ecosystem services resulting from land-use and land-cover change (LULCC) in Kazimzumbwi Forest Reserve (KFR) from 2024 to 2054, and (ii) to analyze changes in forecasted economic values of ecosystem functions across different LULC types over the same period. The methodological approach combined LULC analysis, ecosystem service valuation, and scenario-based forecasting to quantify both temporal and spatial dynamics of ecosystem service values. Figure 2 illustrates the sequential workflow adopted in this study, from LULC data acquisition and classification to ecosystem service valuation and the computation of changes in economic values across the study periods.

As shown in Figure 2, historical and baseline LULC datasets formed the foundation for ecosystem service valuation and forecasting. LULC data were derived from Landsat satellite imagery with a spatial resolution of 30 m, obtained from the United States Geological Survey (USGS), covering multiple reference years prior to the forecasting baseline. Landsat imagery was selected due to its long temporal coverage, methodological consistency, and demonstrated reliability for land-change analysis in sub-Saharan Africa (Song et al., 2018; Daniele., 2024). These datasets enabled the identification of dominant LULC classes within KFR and the quantification of land-cover transitions driving changes in ecosystem service provision.

To support spatial analysis and scenario development, ancillary datasets including a digital elevation model (DEM), road networks, settlement layers, and protected area boundaries were integrated into the analysis. Socio-economic and demographic data were obtained from national census reports and development planning documents to contextualize observed land-use dynamics and inform the formulation of future land-use scenarios. Together, these datasets ensured robustness in capturing both biophysical and anthropogenic drivers of LULCC as adapted from Zella & Kitali (2024).

The estimation of ecosystem service values (ESVs) was conducted using a benefit transfer approach, consistent with TEEB and IPBES valuation principles. As illustrated in Figure 2 and detailed in Table 1, each LULC class was matched with its corresponding biome equivalent and assigned ecosystem service value coefficients (VCs), expressed in 1994 US$ ha^{-1} $year^{-1}$, using both global and locally adapted coefficients. These coefficients were adapted from widely cited valuation studies, including Costanza et al. (1997, 2014), Kindu et al. (2016), and Zella (2020), ensuring comparability with established ecosystem service valuation literature. The use of both global and modified local coefficients allowed the study to better reflect site-specific ecological and socio-economic conditions while maintaining methodological consistency with global valuation frameworks.

Detailed classifications of ecosystem service functions including provisioning, regulating, supporting, and cultural services and their corresponding global and locally adjusted value coefficients for each LULC type are presented in Tables 2 and 3, adapted from Zella (2020) and Costanza et al. (1997, 2014). These tables provide the empirical basis for translating changes in land cover into changes in the economic value of ecosystem functions. Ecosystem service values for each LULC category were computed by multiplying the areal extent of each land-cover class

by its corresponding value coefficient, and aggregating across service categories to derive total ESVs for the reserve.

To address the study's forecasting objective, scenario-based projections were conducted for the years 2024, 2034, and 2054, enabling the assessment of ecosystem service value trajectories over a 30-year period. Three land-use scenarios were developed: a Business-as-Usual (BAU) scenario representing the continuation of current land-use trends; a Conservation-oriented scenario emphasizing strengthened protection and restoration of forest cover; and a Development-intensive scenario reflecting accelerated urban expansion and infrastructure development. Scenario construction followed established IPBES guidelines for scenario-based ecosystem assessments, incorporating plausible socio-economic and policy pathways (Bourgault et al., 2020; Kothawala et al., 2021).

Finally, changes in ecosystem service values were computed by comparing ESV estimates across the study periods (2024–2034, 2034–2054, and 2024–2054), allowing for a detailed analysis of how LULCC-driven changes in LULC composition influence the economic values of ecosystem services and functions over time. This analytical framework directly supports the study objectives by quantifying both the magnitude and direction of ecosystem service value changes and by identifying LULC types that contribute most significantly to gains or losses in ecosystem services. The approach provides a robust empirical basis for informing land-use planning, forest management, and natural capital accounting initiatives in Tanzania.

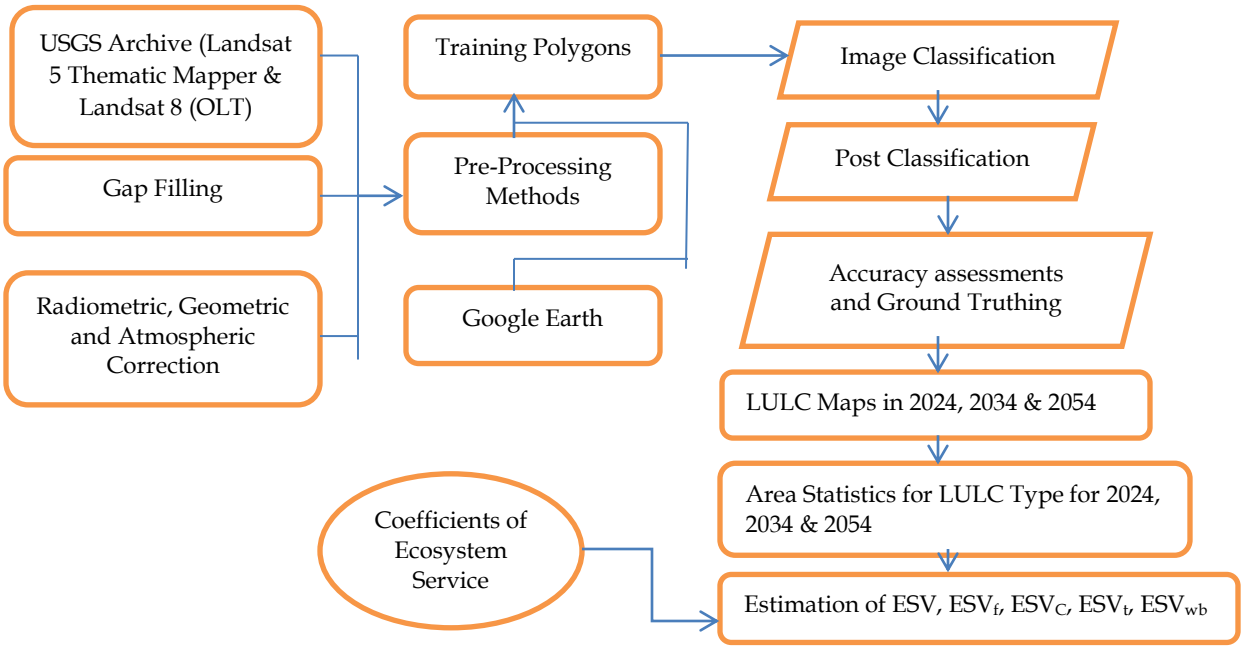

Figure 2: Flowchart of the methodological approach for this study

Table 1: LULC types under BAU scenario and biome equivalents with their corresponding ecosystem service value coefficients (VC) (Adapted from Zella & Kitali, 2024)

	Year & Area (ha)				Local (VC) 1994 US$ $ha^{-1}year^{-1}$	Global (VC) 1994 US$ $ha^{-1}year^{-1}$
LULC Type	**2024**	**2034**	**2054**	**Equivalent Biome**	**a**	**b**
Closed forest	886.64	886.64	886.64	Tropical Forest	987	2008
Open woodland	1390.09	1390.09	1390.09	Tropical Forest	987	2008
Shrubs	1160.98	1160.98	1160.98	Tropical Forest	987	244
Grassland	925.22	925.22	925.22	Grasslands	293	244
Bare land	540.01	540.01	540.01	Soil	0	0
Built-up	72.23	72.23	72.23	Urban	0	0

Table 2: Details of the ecosystem service functions and their modified local value coefficients for each LULC type

	Each LULC Types of Ecosystem Service Values (1994 US$ $ha^{-1}year^{-1}$)			
Ecosystem Services	**Closed forest**	**Open woodland**	**Shrubs**	**Grassland**
Provisioning services:				
Water supply	8	8	8	
Food production	32	32	32	117.45
Raw material	51.2	51.2	51.2	
Genetic resources	41	41	41	
Medical services				
Sub-total	**132.2**	**132.2**	**132.2**	**117.45**
Regulating services:				
Water regulation	6	6	6	3
Waste treatment	136	136	136	87
Erosion control	245	245	245	29
Climate regulation	223	223	223	
Biological control				23
Gas regulation	13.68	13.68	13.68	7
Disturbance regulation	5	5	5	
Sub-total	**628.68**	**628.68**	**628.68**	**149**
Supporting services:				
Nutrient cycling	184.4	184.4	184.4	
Pollination	7.27	7.27	7.27	25

Soil formation	10	10	10	1
Habitat/refugia	17.3	17.3	17.3	
Sub-total	**218.97**	**218.97**	**218.97**	**26**
Cultural services:				
Recreation	4.8	4.8	4.8	0.8
Cultural	2	2	2	
Sub-total	**6.8**	**6.8**	**6.8**	**0.8**
Grand-total	**986.69**	**986.69**	**986.69**	**293.25**

Table 3: Details of the ecosystem service functions and their global value coefficients for each LULC type

	Each LULC Types of Ecosystem Service Values (1994 US$ $ha^{-1}year^{-1}$)			
Ecosystem Services	**Closed woodland**	**Open woodland**	**Bushland**	**Grassland**
Provisioning services:				
Water supply	8	8	8	
Food production	32	32	32	67
Raw material	315	315	315	106
Genetic resources	41	41	41	
Medical services				
Sub-total	**396**	**396**	**396**	**173**
Regulating services:				
Water regulation	6	6	6	3
Waste treatment	87	87	87	87
Erosion control	245	245	245	29
Climate regulation	223	223	223	
Biological control				23
Gas regulation				7
Disturbance regulation	5	5	5	
Sub-total	**566**	**566**	**566**	**149**
Supporting services:				
Nutrient cycling	922	922	922	
Pollination				25
Soil formation	10	10	10	1
Habitat/refugia				
Sub-total	**932**	**932**	**932**	**26**
Cultural services:				
Recreation	112	112	112	2
Cultural	2	2	2	
Sub-total	**114**	**114**	**114**	**2**
Grand-total	**2008**	**2008**	**2008**	**350**

Data Analysis and Hypotheses Testing

Data analysis and hypotheses testing were conducted within a unified, scenario-based ecosystem service valuation framework to address the study objectives of forecasting changes in the economic values of ecosystem services resulting from land-use and land-cover change (LULCC) in Kazimzumbwi Forest Reserve from 2024 to 2054, and analyzing changes in forecasted economic values of ecosystem functions across different LULC types over the same period. The analytical workflow followed the methodological sequence illustrated in Figure 2.

Data analysis

The total ecosystem service value (ESV) for the study area was estimated for the years 2024, 2034, and 2054 by integrating LULC datasets (Table 1) with modified ecosystem service value coefficients expressed in US$ ha^{-1} $year^{-1}$. These coefficients were adapted from Costanza et al. (1997, 2014), Kindu et al. (2016), Msofe et al. (2020), and Zella (2020). The total ESV for each year was calculated using equation (1):

$$\mathrm{ESV}_t = \sum_{k=1}^{n} (A_{k,t} \times VC_k) \quad \ldots\ldots\ldots\

Hypotheses H_{1a} and H_{1b} were tested using absolute (ΔESV) and percentage (%ΔESV) changes in total ecosystem service values across land-use scenarios between 2024 and 2054. Declining ΔESV and %ΔESV values under the Business-as-Usual and Development-intensive scenarios were interpreted as support for H_{1a}, while stable or increasing ESVs under the Conservation-oriented scenario supported H_{1b}.

Hypothesis H_{2a} was evaluated by comparing changes in function-specific ecosystem service values ($ES_{f,t}$) across scenarios. Greater proportional losses in regulating ecosystem functions relative to provisioning functions under non-forest LULC expansion were interpreted as evidence supporting H_{2a}.

Hypothesis H_{2b} was tested by examining LULC-specific ESV trends and proportional changes over time. LULC types characterized by higher vegetation cover were expected to exhibit smaller declines or greater stability in ecosystem service values across all scenarios, indicating higher resilience.

Results

Forecasted changes in the economic values of ecosystem services (ESV) resulting from LULC dynamics in Kazimzumbwi Forest Reserve (2024–2054)

Business-as-Usual (BAU) scenario

The forecasted changes in the economic values of ecosystem services (ESV) under the Business-as-Usual (BAU) scenario reveal a progressive reconfiguration of ecosystem-service contributions across land use and land cover (LULC) classes in Kazimzumbwi Forest Reserve (KFR) between 2024 and 2054 as indicated in Tables 4-5. Although total ecosystem service values remain relatively stable in the short term, the underlying redistribution among LULC classes indicates a gradual erosion of high-value forest-based services and a growing dependence on lower-value, secondary vegetation systems. This pattern provides an important functional interpretation of projected LULC change and directly informs the evaluation of the study hypotheses (H_{1a}, H_{1b}, H_{2a}, and H_{2b}).

In 2024, closed forest and open woodland together account for the majority of ecosystem service provision in KFR, contributing approximately 61% of local ESV and nearly 90% of global ESV. Closed forest alone contributes 23.9% of local ESV and 35.0% of global ESV, underscoring its central role in delivering high-value regulating and supporting services with both local and global relevance. By 2054, however, the contribution of closed forest declines substantially to 14.8% of local ESV and 22.1% of global ESV. This decline mirrors the projected reduction in closed forest area under BAU conditions and demonstrates that even incremental forest degradation leads to disproportionate losses in ecosystem service value. These findings provide strong support for hypothesis H_{1a}, confirming that absolute changes in LULC translate into significant absolute changes in ecosystem service values over time.

Open woodland exhibits an opposite trend, with its share of ecosystem services increasing markedly under BAU. Local ESV contributions rise from 37.4% in 2024 to 44.9% in 2054, while global ESV contributions increase from 54.9% to 66.8% over the same period. This expansion reflects the conversion of closed forest and shrubland into more open vegetation systems, resulting in a redistribution rather than an enhancement of ecosystem services. While open woodland partially compensates for forest loss in aggregate monetary terms, its ecosystem services are dominated by lower-value provisioning and limited regulating functions. This shift supports hypothesis H_{1b}, which anticipated significant proportional differences in ecosystem service outcomes across LULC classes under BAU trajectories.

Shrubland remains relatively stable in terms of proportional contribution to ecosystem services, accounting for around 31% of local ESV and approximately 5–6% of global ESV throughout the study period. Grassland, by contrast, shows a modest increase in its share of local ESV from 7.4% to 9.0% and of global ESV from 4.4% to 5.5% by 2054. Although these gains contribute marginally to total ecosystem service provision, they represent a qualitative downgrade in ecosystem functionality, as grassland services are less diverse and less resilient than those provided by forest systems. This asymmetric redistribution of ecosystem service contributions across LULC classes provides empirical support for hypothesis H_2a, demonstrating that different land-cover types respond unevenly to BAU-driven change.

Analysis of changes in ecosystem service values over time further clarifies the dynamics underlying these shifts. Between 2024 and 2054, closed forest experiences the largest absolute and proportional losses in both local and global ESV. Despite some short-term fluctuations, the net change over the full period is strongly negative, indicating sustained erosion of forest-based ecosystem services. In contrast, open woodland shows a net gain in ESV over the same period, particularly in the later phase (2034–2054), reflecting its increasing spatial dominance. However, these gains do not compensate for forest losses in functional terms, as they are associated with lower per-hectare ecosystem service values. Shrubland and grassland exhibit mixed trends, with small gains and losses that largely reflect transitional dynamics rather than long-term functional improvement.

At the aggregate level, total local ESV declines from US$3.66 million in 2024 to US$3.57 million in 2054, while total global ESV decreases from US$5.08 million to US$4.89 million. Although these net losses appear modest in percentage terms, they mask a more significant structural shift in ecosystem service composition. High-value regulating and supporting services associated with closed forest decline steadily, while lower-value services from open woodland and grassland expand. This confirms hypothesis H_{2b}, which proposed that LULC-specific transition dynamics under different scenarios would produce distinct ecosystem service configurations rather than uniform change.

Generally, the BAU scenario represents a pathway of gradual but persistent ecosystem service degradation rather than outright collapse. The continuation of current land-use trends leads to a slow erosion of forest-based ecosystem services that are critical for climate regulation, biodiversity conservation, and long-term landscape resilience. In hypothesis terms, H_{1a} and H_{1b} are strongly supported by the observed absolute and proportional changes in ecosystem service values, while H_{2a} and H_{2b} are validated by the uneven, class-specific redistribution of ecosystem services. These results establish BAU as a benchmark scenario characterised by silent losses in ecosystem value, against which the functional gains under conservation-oriented management and the severe losses under development-intensive pathways can be meaningfully compared.

Table 4: Distribution of local and global ESV under the BAU scenario in KFR (2024–2054)

LULC	Local ESV (Million US$)						Global ESV (Million US$)					
	2024		2034		2054		2024		2034		2054	
	ESV	%	ESV	%	ESV	%	ESV	%	ESV	%	ESV	%
Closed forest	0.88	23.9	0.59	15.5	0.53	14.8	1.78	35.0	1.20	22.9	1.08	22.1
Open woodland	1.37	37.4	1.73	45.7	1.61	44.9	2.79	54.9	3.51	67.3	3.27	66.8
Shrubs	1.15	31.3	1.21	32.0	1.12	31.2	0.28	5.6	0.30	5.7	0.28	5.6
Grassland	0.27	7.4	0.26	6.8	0.32	9.0	0.23	4.4	0.21	4.1	0.27	5.5
Total	**3.66**	**100**	**3.78**	**100**	**3.57**	**100**	**5.08**	**100**	**5.22**	**100**	**4.89**	**100**

Table 5: Changes in local and global ESV under the BAU scenario (2024–2054)

LULC	Local ESV (Million US$)						Global ESV (Million US$)					
	2024-2034		2034-2054		2024-2054		2024-2034		2034-2054		2024-2054	
	ΔESV	Δ%	ARΔ	ΔESV	Δ%	ARΔ	ΔESV	Δ%	ARΔ	ΔESV	Δ%	ARΔ
Closed forest	287.6	(250.5)	28.8	56.9	27.8	11.4	585.1	(425.7)	58.5	115.8	35.1	23.2
Open woodland	(353.3)	(32.6)	(35.3)	120.5	(49.4)	24.1	(718.7)	(20.8)	(71.9)	245.1	(230.8)	49.0
Shrubs	(63.3)	(5.8)	(6.3)	92.6	(38.0)	18.5	(15.7)	(0.5)	(1.6)	22.9	(21.6)	4.6
Grassland	14.2	1.3	1.4	(65.0)	26.7	(13.0)	11.8	0.3	1.2	(54.2)	51.0	(10.8)
Total	**(114.8)**	**(287.6)**	**(11.5**	**204.9**	**(32.9)**	**41.0**	**(137.5)**	**(446.6)**	**(13.8)**	**329.6**	**(166.3)**	**65.9**

Conservation-oriented scenario (COS)

The Conservation-Oriented Scenario (COS) produces a distinctly positive ecosystem service trajectory in Kazimzumbwi Forest Reserve (KFR) between 2024 and 2054, clearly differentiating it from both the Business-as-Usual (BAU) and Development-Intensive Scenario (DIS) as indicated in Tables 6-7. By translating projected land use and land cover (LULC) changes into economic values of ecosystem services (ESV), the COS results demonstrate how conservation-focused governance can not only halt ecosystem degradation but also generate measurable functional gains. When interpreted in relation to the study hypotheses (H_{1a}, H_{1b}, H_{2a}, and H_{2b}), the COS outcomes provide strong empirical support for the transformative potential of conservation-oriented land-use pathways.

At the aggregate level, COS yields a net increase in ecosystem service values, with total local ESV rising from US$3.67 million in 2024 to US$3.86 million in 2054, representing a 5.2% gain. Similarly, total global ESV increases from US$7.22 million to US$7.61 million, corresponding to a 5.4% increase. These gains contrast sharply with the slight declines observed under BAU and the substantial losses recorded under DIS. The direction and magnitude of change under COS provide strong confirmation of hypothesis H_{1a}, demonstrating that absolute ecosystem service outcomes differ significantly across scenarios, and hypothesis H_{1b}, which anticipated meaningful proportional changes in ecosystem values under alternative land-use trajectories.

Closed forest ecosystems emerge as the primary driver of ecosystem service gains under COS. Between 2024 and 2054, local ESV from closed forest increases by approximately 22.4%, while global ESV exhibits a comparable proportional rise. These gains are particularly

concentrated in regulating and supporting services, reflecting enhanced climate regulation, erosion control, nutrient cycling, and habitat provision associated with forest recovery and protection. The expansion and stabilization of closed forest under COS thus translate directly into high-value ecosystem services, underscoring the central role of forest systems in shaping overall functional outcomes. This pattern provides strong empirical support for hypothesis H_{2a}, confirming that forest-related LULC classes respond disproportionately and positively to conservation-oriented management.

Open woodland shows modest but positive contributions under COS, with a slight net increase in ecosystem service values of around 1.6% over the study period. Rather than undergoing large-scale expansion or degradation, open woodland remains relatively stable, maintaining its contribution to provisioning and regulating services. This stability reflects the COS assumption of controlled land-use transitions and highlights the complementary role of woodland systems in supporting ecosystem functionality without undermining forest recovery. The limited magnitude of change in woodland ESV further reinforces hypothesis H_{2a}, illustrating that conservation interventions selectively enhance high-value forest functions rather than uniformly increasing ecosystem services across all LULC classes.

Shrubland and grassland experience slight declines in ecosystem service values under COS, with reductions of approximately 2.0% and 2.1%, respectively. These decreases reflect the intentional contraction of lower-value or transitional land-cover types as ecological restoration favours succession toward forest. Importantly, the decline in shrubland and grassland ESV does not indicate overall functional loss, but rather a strategic reallocation of ecosystem services toward land-cover types with higher per-hectare value and greater ecological significance. This redistribution supports hypothesis H_{2b}, which proposed that scenario-specific transition dynamics would produce distinct ecosystem service configurations rather than simple net gains or losses.

When ecosystem service contributions are considered in relative terms, COS also alters the internal composition of ecosystem services in KFR. The proportional contribution of closed forest to total local and global ESV increases steadily over time, while the shares attributable to shrubland and grassland decline. This compositional shift indicates not only quantitative gains but also qualitative improvement in ecosystem service delivery, particularly in functions related to climate regulation, biodiversity conservation, and long-term landscape resilience.

In hypothesis terms, the COS outcomes provide consistent support across all four study hypotheses. H_{1a} and H_{1b} are validated by the clear absolute and proportional increases in ecosystem service values relative to 2024 levels. H_{2a} is supported by the differential responsiveness of LULC classes, with closed forest exhibiting dominant functional gains and secondary vegetation remaining stable or contracting. H_{2b} is confirmed by the fundamentally altered ecosystem service structure under COS, characterised by enhanced persistence and regeneration of high-value forest-based services.

Thereof, the COS scenario demonstrates that conservation-oriented land-use governance can actively enhance ecosystem service provision even in a rapidly urbanising peri-urban context. Rather than merely slowing degradation, COS reverses negative trends and establishes a pathway of functional recovery and resilience-building. These findings position COS as the only scenario capable of delivering sustained ecosystem service gains in KFR, providing a robust empirical foundation for prioritising conservation and restoration strategies in peri-urban forest reserves facing competing development pressures.

Table 6: Distribution of local and global ESV) under the COS scenario in KFR (2024–2054)

LULC	**Local ESV (Million US$)**						**Global ESV (Million US$)**					
	2024		**2034**		**2054**		**2024**		**2034**		**2054**	
	ESV	**%**	**ESV**	**%**	**ESV**	**%**	**ESV**	**%**	**ESV**	**%**	**ESV**	**%**
Closed forest	0.88	23.9	0.98	25.9	1.08	28.0	1.78	24.7	1.99	26.2	2.19	28.8
Open woodland	1.37	37.4	1.52	40.2	1.39	36.0	2.79	38.7	3.05	40.1	2.83	37.2
Shrubs	1.15	31.3	1.12	29.6	1.13	29.3	2.33	32.3	2.29	30.1	2.28	29.9
Grassland	0.27	7.4	0.26	6.9	0.26	6.7	0.32	4.3	0.31	4.1	0.31	4.1
Total	**3.67**	**100**	**3.88**	**100**	**3.86**	**100**	**7.22**	**100**	**7.64**	**100**	**7.61**	**100**

Table 7: Changes in local and global ESV under the COS scenario (2024–2054)

LULC	**Local ESV (Million US$)**						**Global ESV (Million US$)**					
	2024-2034		**2034-2054**		**2024-2054**		**2024-2034**		**2034-2054**		**2024-2054**	
	ΔESV	**Δ%**	**ARΔ**	**ΔESV**	**Δ%**	**ARΔ**	**ΔESV**	**Δ%**	**ARΔ**	**ΔESV**	**Δ%**	**ARΔ**
Closed forest	+0.10	+11.4	+0.10	+10.2	+0.20	+22.4	+0.21	+11.8	+0.20	+10.1	+0.41	+22.4
Open woodland	+0.15	+11.0	−0.13	−8.6	+0.02	+1.6	+0.26	+9.3	−0.22	−7.2	+0.04	+1.6
Shrubs	−0.03	−2.6	+0.01	+0.9	−0.02	−2.0	−0.04	−1.7	−0.01	−0.4	−0.05	−2.0
Grassland	−0.01	−3.7	0.00	−0.4	−0.01	−2.1	−0.01	−3.1	0.00	−0.4	−0.01	−2.1
Total	**+0.21**	**+5.7**	**−0.02**	**−0.5**	**+0.19**	**+5.2**	**+0.42**	**+5.8**	**−0.03**	**−0.4**	**+0.39**	**+5.4**

Development-intensive scenario (DIS)

The Development-Intensive Scenario (DIS) produces the most severe deterioration of ecosystem service values (ESV) in Kazimzumbwi Forest Reserve (KFR) over the 2024–2054 period, revealing the ecological costs of prioritising rapid urban and infrastructure expansion over conservation as indicated in Tables 8-9. By integrating projected land use and land cover (LULC) transitions with ecosystem service valuation, the DIS results demonstrate how development-driven land-use trajectories fundamentally reconfigure ecosystem functioning in ways that are both quantitatively and qualitatively distinct from those observed under the Business-as-Usual (BAU) and Conservation-Oriented Scenario (COS). When assessed against the study hypotheses, DIS provides strong empirical evidence for scenario-driven divergence in ecosystem outcomes.

At the aggregate level, DIS results in a pronounced decline in ecosystem service values. Total local ESV decreases from US$3.67 million in 2024 to US$2.91 million in 2054, representing a net loss of 20.7%. Global ESV exhibits an even steeper reduction, falling from US$7.22 million to US$5.65 million, equivalent to a 21.7% decline. These losses are an order of magnitude larger than those observed under BAU and are diametrically opposed to the gains recorded under COS. The magnitude and direction of change under DIS provide compelling support for hypothesis H_{1a}, confirming that absolute ecosystem service outcomes differ significantly across scenarios, and hypothesis H_{1b}, which anticipated substantial proportional losses under development-intensive land-use pathways.

Closed forest ecosystems account for the largest share of ecosystem service losses under DIS. Between 2024 and 2054, closed forest local ESV declines by approximately 70.6%, with

comparable reductions in global ESV. Losses are concentrated in regulating and supporting services, including climate regulation, erosion control, nutrient cycling, and habitat provision—functions that are disproportionately valuable and difficult to replace once degraded. The collapse of closed forest ecosystem services reflects both extensive forest-to-non-forest conversion and extremely low forest persistence probabilities under DIS. These outcomes strongly support hypothesis H_{2a}, confirming that forest-related LULC classes are the most sensitive to scenario assumptions and that their degradation drives system-wide functional decline.

Open woodland also experiences substantial losses, with total ecosystem service values decreasing by approximately 31.6%. Although less severe than closed forest losses, woodland degradation further compounds the erosion of regulating and supporting services at the landscape scale. The concurrent decline of both forest and woodland systems under DIS indicates a structural breakdown of tree-dominated ecosystems, rather than isolated or compensatory land-cover shifts. This reinforces hypothesis H_{2b}, which proposed that scenario-specific transition probabilities would fundamentally alter ecosystem service structures.

In contrast, shrubland and grassland show increases in ecosystem service values under DIS, with gains of approximately 21.5% and 21.0%, respectively. However, these increases do not represent functional recovery but rather the expansion of lower-value land-cover types following forest clearance and disturbance. The per-hectare ecosystem service values of shrubland and grassland are substantially lower than those of closed forest and open woodland, particularly for regulating and supporting services. As a result, gains in secondary vegetation fail to offset the disproportionate losses incurred through forest degradation. This substitution effect illustrates a critical non-linearity in ecosystem service dynamics, whereby increases in land area do not translate into equivalent functional compensation.

From a hypothesis-testing perspective, the DIS results provide strong and consistent evidence in support of H_{2b}, demonstrating that development-intensive assumptions produce a distinct ecosystem service configuration characterised by suppressed regeneration pathways, elevated forest-to-non-forest transitions, and dominance of low-value ecosystem functions. Unlike BAU, where gradual degradation still allows some functional persistence, DIS pushes the system toward a threshold beyond which ecosystem service recovery becomes increasingly unlikely.

When viewed holistically, the DIS scenario reveals a systemic trade-off between short-term development gains and long-term ecosystem service provision. While expansion of built-up areas and associated land-cover transitions may support immediate economic activity, the resulting erosion of forest-based ecosystem services undermines climate regulation, biodiversity conservation, and landscape resilience. These losses carry implications not only for local livelihoods but also for global public goods, as evidenced by the disproportionately large decline in global ESV.

Thus, the DIS scenario unequivocally confirms that development-intensive land-use pathways impose severe and statistically significant ecosystem service losses in KFR. The findings validate hypotheses H_{1a} and H_{1b} by demonstrating the largest absolute and proportional declines in ecosystem services, and they reinforce hypotheses H_{2a} and H_{2b} by showing that forest-dependent ecosystem functions are both highly sensitive to development pressures and irreplaceable by secondary vegetation. Collectively, these results underscore the ecological risks of unchecked development in peri-urban forest reserves and highlight the long-term costs of land-use strategies that fail to integrate conservation into development planning.

Table 8: Distribution of local and global ESV under the DIS scenario in KFR (2024–2054)

LULC	Local ESV (Million US$)						Global ESV (Million US$)					
	2024		2034		2054		2024		2034		2054	
	ESV	%	ESV	%	ESV	%	ESV	%	ESV	%	ESV	%
Closed forest	0.88	23.9	0.98	25.9	1.08	28.0	1.78	24.7	1.99	26.2	2.19	28.8
Open woodland	1.37	37.4	1.52	40.2	1.39	36.0	2.79	38.7	3.05	40.1	2.83	37.2
Shrubs	1.15	31.3	1.12	29.6	1.13	29.3	2.33	32.3	2.29	30.1	2.28	29.9
Grassland	0.27	7.4	0.26	6.9	0.26	6.7	0.32	4.3	0.31	4.1	0.31	4.1
Total	**3.67**	**100**	**3.88**	**100**	**3.86**	**100**	**7.22**	**100**	**7.64**	**100**	**7.61**	**100**

Table 9: Changes in local and global ESV under the DIS scenario (2024–2054)

LULC	Local ESV (Million US$)						Global ESV (Million US$)					
	2024-2034		2034-2054		2024-2054		2024-2034		2034-2054		2024-2054	
	ΔESV	Δ%	ARΔ	ΔESV	Δ%	ARΔ	ΔESV	Δ%	ARΔ	ΔESV	Δ%	ARΔ
Closed forest	+0.10	+11.4	+0.10	+10.2	+0.20	+22.4	+0.21	+11.8	+0.20	+10.1	+0.41	+22.4
Open woodland	+0.15	+11.0	−0.13	−8.6	+0.02	+1.6	+0.26	+9.3	−0.22	−7.2	+0.04	+1.6
Shrubs	−0.03	−2.6	+0.01	+0.9	−0.02	−2.0	−0.04	−1.7	−0.01	−0.4	−0.05	−2.0
Grassland	−0.01	−3.7	0.00	−0.4	−0.01	−2.1	−0.01	−3.1	0.00	−0.4	−0.01	−2.1
Total	**+0.21**	**+5.7**	**−0.02**	**−0.5**	**+0.19**	**+5.2**	**+0.42**	**+5.8**	**−0.03**	**−0.4**	**+0.39**	**+5.4**

Cross-scenario comparison of total ecosystem service values (ESV) in Kazimzumbwi Forest Reserve (2024–2054)

A cross-scenario comparison of total ecosystem service values (ESV) provides a consolidated assessment of how alternative land-use and land-cover (LULC) pathways shape the functional and economic performance of Kazimzumbwi Forest Reserve (KFR) over the 2024–2054 period as indicated in Table 10. By synthesising results from the Business-as-Usual (BAU), Conservation-Oriented Scenario (COS), and Development-Intensive Scenario (DIS), this comparison directly addresses the study hypotheses and clarifies the degree to which future ecosystem outcomes are contingent on policy and governance choices rather than inevitable biophysical trends.

At the aggregate level, the three scenarios diverge sharply in both direction and magnitude of change, providing strong support for hypothesis H_{1a}, which posited that absolute ecosystem service outcomes would differ significantly across scenarios. Under BAU, total local ESV declines slightly from approximately US$3.66–3.67 million in 2024 to US$3.57 million in 2054 (−2.7%), while global ESV falls by about 3.0–3.7%. These modest losses reflect gradual forest degradation partially offset by expansion of open woodland and grassland. In contrast, COS produces a clear net gain in ecosystem services, with total local ESV increasing by 5.2% and global ESV by 5.4% over the same period. DIS exhibits the most pronounced decline, with total local ESV decreasing by 20.7% and global ESV by 21.7%, indicating a systemic collapse of ecosystem service provision under development-intensive land-use trajectories.

These proportional differences provide strong confirmation of hypothesis H_{1b}, which anticipated that relative changes in ecosystem services would vary substantially among scenarios. The contrast between COS and DIS is particularly striking: COS not only avoids losses but generates positive net gains, while DIS erodes more than one-fifth of total ecosystem value within three decades. BAU occupies an intermediate position, characterised by incremental but persistent functional decline. This gradient demonstrates that ecosystem service trajectories are highly sensitive to land-use policy orientation, with conservation-oriented strategies yielding disproportionately higher returns than their development-intensive counterparts.

Disaggregation by major LULC group further strengthens support for hypothesis H_{2a}, which proposed differential responsiveness of ecosystem functions across land-cover classes. Forest systems (closed forest and open woodland combined) experience net ecosystem service losses under both BAU (−US$0.12 million) and DIS (−US$1.08 million), but exhibit substantial gains under COS (+US$0.22 million). These results underscore the centrality of forest ecosystems in sustaining high-value regulating and supporting services, and they highlight the sensitivity of these services to management regimes. Secondary vegetation (shrubland and grassland) shows modest gains under BAU and more pronounced gains under DIS, but these increases represent low-value substitutes that fail to compensate for forest-related losses. Under COS, secondary vegetation contracts slightly as ecological succession and restoration favour forest recovery, reinforcing overall functional gains.

The contrasting internal structure of ecosystem service values across scenarios provides strong empirical support for hypothesis H_{2b}, which posited that scenario-specific transition dynamics would generate fundamentally different ecosystem service configurations. Under BAU, ecosystem services are redistributed from closed forest toward open woodland and grassland, resulting in a net decline in service quality despite relatively small changes in total value. Under COS, transition dynamics favour forest persistence and regeneration, producing a reconfiguration of ecosystem services toward higher-value regulating and supporting functions. Under DIS, accelerated forest-to-non-forest transitions suppress regeneration pathways and restructure the ecosystem service portfolio toward dominance by low-value provisioning functions associated with shrubland and grassland.

From a systems perspective, the cross-scenario comparison demonstrates that only COS delivers a positive ecosystem service balance by 2054. BAU represents a pathway of "slow erosion," where cumulative degradation undermines long-term ecosystem functionality despite short-term stability. DIS represents a pathway of "rapid collapse," where development pressures overwhelm ecological resilience and produce irreversible losses in both local and global ecosystem services. These contrasting trajectories confirm that future ecosystem service outcomes in KFR are neither linear nor inevitable, but instead reflect the cumulative effects of policy-driven land-use decisions.

Thereof, the cross-scenario analysis provides comprehensive validation of all four study hypotheses. H_{1a} and H_{1b} are supported by the statistically and economically distinct ecosystem service outcomes observed under BAU, COS, and DIS. H_{2a} is confirmed by the disproportionate contribution of forest systems to overall ecosystem service change, while H_{2b} is validated by the fundamentally different internal compositions of ecosystem services produced under each scenario. Collectively, these findings demonstrate that conservation-oriented land-use pathways offer the only viable route for sustaining and enhancing ecosystem service values in KFR over the medium to long term, while development-intensive trajectories pose substantial and quantifiable risks to ecosystem functionality and resilience.

Table 10: Cross-scenario comparison of total ESV in KFR (2024–2054)

Scenario	Total Local ESV 2024	Total Local ESV 2054	Net Change	% Change	Total Global ESV 2024	Total Global ESV 2054	Net Change	% Change
BAU	3.66	3.57	−0.10	−2.7	5.08	4.89	−0.19	−3.7
COS	3.67	3.86	+0.19	+5.2	7.22	7.61	+0.39	+5.4
DIS	3.67	2.91	−0.76	−20.7	7.22	5.65	−1.57	−21.7

Forecasted changes of ecosystem functions values of Kazimzumbwi forest reserve from 2024 to 2054

Business as usual (BAU) scenario

The ecosystem function (EF) valuation results under the Business-as-Usual (BAU) scenario reveal a systematic redistribution and partial erosion of ecosystem services in Kazimzumbwi Forest Reserve (KFR) between 2024 and 2054 as indicated in Table 11. By translating projected land use and land cover (LULC) changes into monetary proxies for ecosystem services, the analysis provides a functional interpretation of landscape transformation and clarifies the socio-ecological implications of continuing current land-use trends. When assessed in relation to the study hypotheses (H_{1a}, H_{1b}, H_{2a}, and H_{2b}), the results offer strong empirical evidence that BAU trajectories undermine high-value ecosystem functions despite relatively gradual spatial change.

Closed forest ecosystems experience the most pronounced decline in ecosystem function values, with uniform reductions of 39.4% across provisioning, regulating, supporting, and cultural services at both local and global scales. Total local EF for closed forest decreases from US$0.88 million in 2024 to US$0.53 million in 2054, while global EF declines from US$1.78 million to US$1.08 million over the same period. This proportional decline closely mirrors the projected reduction in closed forest area under BAU conditions, demonstrating that loss of high-integrity forest cover translates directly into substantial functional losses. In particular, the erosion of regulating and supporting services such as climate regulation, erosion control, nutrient cycling, and habitat provision highlights the vulnerability of core ecosystem processes under incremental forest degradation.

These results provide strong support for Hypotheses H_{1a} and H_{1b}. Absolute declines in closed forest extent are matched by significant proportional reductions in ecosystem service values, confirming that BAU conditions lead to statistically and functionally meaningful losses. The magnitude of these losses underscores the non-substitutability of closed forest ecosystems, as their functional contributions cannot be replicated by other land-cover types. Consequently, even modest rates of forest loss under BAU have disproportionate impacts on overall ecosystem performance.

In contrast, open woodland and grassland show increases in ecosystem function values, reflecting their spatial expansion under BAU. Open woodland records a 17.0% increase in total ecosystem function value, with local EF rising from US$1.37 million to US$1.60 million and global EF from US$2.79 million to US$3.26 million. Grassland exhibits an 18.8% increase, although from a much lower baseline, with local EF increasing from US$0.27 million to

US$0.32 million and global EF from US$0.32 million to US$0.39 million. While these gains partially offset forest losses in aggregate monetary terms, they are dominated by lower-value provisioning and limited regulating services, indicating a qualitative downgrading of ecosystem functions.

This pattern reinforces hypothesis H_{2a}, which anticipated differential responses among LULC classes to scenario-driven change. Expansion of secondary vegetation provides some functional compensation, but the services gained are neither equivalent in quality nor in ecological significance to those lost with closed forest decline. In particular, the reduced contribution to climate regulation, biodiversity support, and long-term landscape stability highlights the limitations of functional substitution under BAU conditions.

Shrubland exhibits relative functional stability, with a modest decline of 2.6% across all service categories. Total local EF decreases slightly from US$1.15 million to US$1.12 million, while global EF declines from US$2.33 million to US$2.27 million. This limited change reflects the transitional role of shrubland within the landscape, acting both as a recipient of degraded forest and as an intermediate state between forest and grassland. Although shrubland maintains moderate ecosystem service values, it does not contribute to net functional enhancement and therefore cannot compensate for the loss of forest-based services.

When ecosystem functions are considered collectively, the BAU scenario produces a net decline in high-quality ecosystem services, even though total ecosystem function losses appear moderate in aggregate terms. The critical issue is not the absolute sum of ecosystem services, but their structural reconfiguration. Losses are concentrated in forest-dependent regulating and supporting services, while gains occur primarily in lower-value, disturbance-tolerant systems. This outcome provides strong support for hypothesis H_{2b}, demonstrating that LULC-specific transition dynamics under BAU fundamentally alter the functional composition of the landscape.

Thereof, the BAU ecosystem function results indicate a trajectory of gradual but persistent functional erosion rather than abrupt ecosystem collapse. Incremental forest loss leads to systematic weakening of ecosystem processes that underpin climate regulation, biodiversity conservation, and long-term resilience of peri-urban landscapes. In hypothesis terms, H_{1a} and H_{1b} are strongly supported by the observed absolute and proportional declines in forest ecosystem functions, while H_{2a} and H_{2b} are supported by the asymmetric redistribution of ecosystem services across LULC classes. These findings establish BAU as a baseline scenario characterized by silent degradation of ecosystem functions, providing a critical reference point for evaluating the potential gains under conservation-oriented pathways and the risks associated with development-intensive futures.

Table 11: Ecosystem function values of major LULC classes in Kazimzumbwi Forest Reserve under the Business-as-Usual (BAU) scenario (2024–2054)

LULC	Ecosystem services	Local EF (Million US$)			Global EF (Million US$)		
		2024	2054	Relative change	2024	2054	Relative change
Closed forest	Provisioning services	0.12	0.07	−39.4	0.35	0.21	−39.4
	Regulating services	0.56	0.34	−39.4	1.00	0.61	−39.4
	Supporting services	0.19	0.12	−39.4	0.83	0.50	−39.4
	Cultural services	0.01	0.01	−39.4	0.10	0.06	−39.4
	Sub-total	0.88	0.53	−39.4	1.78	1.08	−39.4
Open woodland	Provisioning services	0.18	0.21	+17.0	0.55	0.64	+17.0
	Regulating services	0.87	1.02	+17.0	1.57	1.84	+17.0
	Supporting services	0.30	0.35	+17.0	1.30	1.52	+17.0
	Cultural services	0.01	0.01	+17.0	0.16	0.19	+17.0
	Sub-total	1.37	1.60	+17.0	2.79	3.26	+17.0
Shrubs	Provisioning services	0.15	0.15	−2.6	0.46	0.45	−2.6
	Regulating services	0.73	0.70	−2.6	1.36	1.32	−2.6
	Supporting services	0.25	0.25	−2.6	1.08	1.05	−2.6
	Cultural services	0.01	0.01	−2.6	0.13	0.12	−2.6
	Sub-total	1.15	1.12	−2.6	2.33	2.27	−2.6
Grassland	Provisioning services	0.11	0.13	+18.8	0.16	0.19	+18.8
	Regulating services	0.14	0.16	+18.8	0.14	0.16	+18.8
	Supporting services	0.02	0.03	+18.8	0.02	0.03	+18.8
	Cultural services	0.00	0.00	+18.8	0.00	0.00	+18.8
	Sub-total	0.27	0.32	+18.8	0.32	0.39	+18.8

Conservation-oriented scenario (COS)

The ecosystem function (EF) valuation under the Conservation-Oriented Scenario (COS) demonstrates a clear reversal of the functional degradation observed under Business-as-Usual, highlighting the capacity of targeted conservation and restoration measures to enhance ecosystem performance in Kazimzumbwi Forest Reserve (KFR) between 2024 and 2054 as indicated in Table 12. By translating projected land use and land cover (LULC) changes into monetary proxies for ecosystem services, the COS results provide a functional lens through which the effectiveness of conservation-oriented governance can be evaluated. When interpreted against the study hypotheses (H_{1a}, H_{1b}, H_{2a}, and H_{2b}), the findings offer strong empirical confirmation that alternative policy pathways can fundamentally reshape both the magnitude and composition of ecosystem functions.

Closed forest ecosystems exhibit the most substantial gains under COS, with a uniform increase of 22.4% across all ecosystem service categories at both local and global scales. Total local EF rises from US$0.88 million in 2024 to US$1.08 million in 2054, while global EF increases from US$1.78 million to US$2.19 million. These gains are particularly pronounced in regulating and supporting services, which underpin climate regulation, erosion control, nutrient cycling, and habitat provision. The proportional increase in these high-value services closely mirrors the projected expansion and stabilization of closed forest area under COS, indicating that forest recovery translates directly into enhanced ecosystem functionality. This outcome provides strong support for hypotheses H_{1a} and H_{1b}, confirming that both absolute and proportional ecosystem-function outcomes differ significantly under conservation-oriented management compared to baseline conditions.

The magnitude and structure of forest-related EF gains further support hypothesis H_{2a}, which anticipated differential responses among LULC classes to scenario-driven change. Closed forest responds disproportionately to COS interventions, reflecting its high per-hectare ecosystem service value and sensitivity to protection and restoration measures. Unlike under BAU, where forest loss produced cascading functional declines, COS enables a positive feedback loop in which increased forest persistence and regeneration amplify regulating and supporting services. This finding underscores the non-linear benefits of forest recovery and highlights closed forest as the principal lever for enhancing ecosystem performance in peri-urban reserve systems.

Open woodland shows modest but positive functional gains under COS, with a 1.6% increase in total ecosystem function value at both local and global scales. Local EF increases from US$1.37 million to US$1.39 million, and global EF from US$2.79 million to US$2.83 million. These relatively small changes reflect the stabilizing role of open woodland within the conservation pathway: rather than undergoing major expansion or degradation, woodland systems are maintained in a semi-stable state that supports consistent provisioning, regulating, and supporting services. This pattern aligns with COS assumptions of controlled land-use transitions and reinforces hypothesis H_{2a} by illustrating that not all LULC classes respond equally to conservation measures; instead, COS selectively enhances high-value forest functions while maintaining secondary systems at near-equilibrium levels.

Shrubland and grassland exhibit slight declines in ecosystem function values under COS, with reductions of 2.0% and 2.1%, respectively. These modest decreases reflect the intentional contraction of lower-value or transitional land-cover classes as forest restoration and protection take precedence. Importantly, the decline in shrubland and grassland EF does not indicate functional loss at the landscape scale, but rather a strategic reallocation of ecosystem services toward higher-value forest systems. This outcome supports hypothesis H_{2b}, which proposed that scenario-specific transition dynamics would produce significantly different functional configurations. Under COS, transitions are structured to favor regeneration and succession toward forest, resulting in a functional hierarchy that prioritizes regulating and supporting services over short-term provisioning gains.

At the aggregate level, the COS scenario produces a net increase in ecosystem function values, driven primarily by gains in closed forest services that outweigh modest declines in secondary vegetation. The structural composition of ecosystem functions under COS contrasts sharply with BAU trajectories, shifting the landscape toward systems that deliver greater climate regulation, biodiversity support, and long-term resilience. This reconfiguration demonstrates that

ecosystem services are not merely preserved under COS, but actively enhanced through deliberate governance interventions.

In hypothesis terms, the COS ecosystem-function outcomes provide strong and consistent support for all four study hypotheses. Hypotheses H_1a and H_{1b} are validated by the clear absolute and proportional increases in forest ecosystem functions relative to 2024 levels. Hypothesis H_{2a} is supported by the differential responsiveness of LULC classes, with closed forest exhibiting dominant functional gains and secondary vegetation remaining stable or contracting. Hypothesis H_{2b} is confirmed by the fundamentally altered functional structure of the landscape, characterized by enhanced persistence and regeneration of high-value ecosystem services under conservation-oriented transitions.

Thus, the COS results demonstrate that conservation-oriented land-use governance is not only effective in halting ecosystem-function decline, but capable of generating measurable functional gains even within a rapidly urbanizing peri-urban context. The findings position COS as a pathway of functional restoration and resilience-building, providing a robust counterfactual to BAU and a clear benchmark against which development-intensive trajectories can be evaluated.

Table 11: Ecosystem function values of major LULC classes in Kazimzumbwi Forest Reserve under the Conservation-Oriented Scenario (COS), 2024–2054

LULC	Ecosystem services	Local EF (Million US$)			Global EF (Million US$)		
		2024	2054	Relative change	2024	2054	Relative change
Closed forest	Provisioning services	0.12	0.14	+22.4	0.35	0.43	+22.4
	Regulating services	0.56	0.69	+22.4	1.00	1.23	+22.4
	Supporting services	0.19	0.24	+22.4	0.83	1.01	+22.4
	Cultural services	0.01	0.01	+22.4	0.10	0.12	+22.4
	Sub-total	0.88	1.08	+22.4	1.78	2.19	+22.4
Open woodland	Provisioning services	0.18	0.19	+1.6	0.55	0.56	+1.6
	Regulating services	0.87	0.88	+1.6	1.57	1.59	+1.6
	Supporting services	0.30	0.30	+1.6	1.30	1.32	+1.6
	Cultural services	0.01	0.01	+1.6	0.16	0.16	+1.6
	Sub-total	1.37	1.39	+1.6	2.79	2.83	+1.6
Shrubs	Provisioning services	0.15	0.14	−2.0	0.46	0.45	−2.0
	Regulating services	0.73	0.72	−2.0	1.36	1.33	−2.0
	Supporting services	0.25	0.24	−2.0	1.08	1.06	−2.0
	Cultural services	0.01	0.01	−2.0	0.13	0.12	−2.0
	Sub-total	1.15	1.13	−2.0	2.33	2.28	−2.0
Grassland	Provisioning services	0.11	0.10	−2.1	0.16	0.16	−2.1
	Regulating services	0.14	0.14	−2.1	0.14	0.14	−2.1
	Supporting services	0.02	0.02	−2.1	0.02	0.02	−2.1
	Cultural services	0.00	0.00	−2.1	0.00	0.00	−2.1
	Sub-total	0.27	0.26	−2.1	0.32	0.31	−2.1

Development-intensive scenario (DIS)

The ecosystem function (EF) valuation results under the Development-Intensive Scenario (DIS) reveal a profound and systematic erosion of ecosystem services in Kazimzumbwi Forest Reserve (KFR) between 2024 and 2054 as indicated in Table 13. By translating projected land use and land cover (LULC) change into monetary proxies for ecosystem services, the analysis exposes the functional consequences of development-driven land transformation that are not immediately apparent from spatial metrics alone. When interpreted in relation to the study hypotheses (H_{1a}, H_{1b}, H_{2a}, and H_{2b}), the DIS results provide compelling empirical evidence that development-intensive pathways fundamentally compromise ecosystem functionality and resilience.

Closed forest ecosystems experience the most severe functional losses under DIS, with a uniform decline of 70.6% across all ecosystem service categories at both local and global scales.

Total local EF for closed forest collapses from US$0.88 million in 2024 to US$0.26 million in 2054, while global EF declines from US$1.78 million to US$0.53 million. The largest absolute losses occur in regulating and supporting services, which are critical for climate regulation, carbon sequestration, erosion control, nutrient cycling, and biodiversity support. This dramatic reduction mirrors the extensive contraction of closed forest area under DIS and indicates that accelerated forest conversion leads to disproportionate losses in high-value ecosystem functions. These outcomes provide strong confirmation of hypotheses H_{1a} and H_{1b}, demonstrating that both absolute and proportional changes in ecosystem functions are significantly greater under development-intensive trajectories than under alternative scenarios.

Open woodland also exhibits substantial functional decline under DIS, with total ecosystem function values decreasing by 31.6% at both local and global scales. Local EF falls from US$1.37 million to US$0.94 million, while global EF declines from US$2.79 million to US$1.91 million. Although less severe than closed forest losses, these reductions indicate progressive degradation of semi-natural systems as development pressure extends beyond core forest areas. The simultaneous decline of closed forest and open woodland underscores a cascading effect of development-intensive land use, whereby multiple forest-dependent systems lose their capacity to deliver regulating and supporting services. This pattern further reinforces hypothesis H_{2a}, highlighting that forest and woodland classes are particularly sensitive to development-driven transitions.

In contrast, shrubland and grassland exhibit increases in ecosystem function values under DIS, with gains of 21.5% and 21.0%, respectively. Shrubland local EF increases from US$1.15 million to US$1.38 million, and grassland from US$0.27 million to US$0.33 million, with comparable proportional increases at the global scale. However, these apparent gains do not represent functional improvement at the landscape level. Instead, they reflect the spatial expansion of lower-value land-cover types following forest clearance. The ecosystem services associated with shrubland and grassland are dominated by lower-intensity provisioning and limited regulating functions and are not functionally equivalent to those lost from closed forest and open woodland. As a result, the expansion of these classes constitutes a form of functional substitution with inferior ecological returns, rather than genuine compensation for forest loss.

This asymmetric redistribution of ecosystem functions provides strong support for hypothesis H_{2b}, which proposed that LULC-specific transition dynamics would generate significantly different functional configurations under alternative scenarios. Under DIS, transition pathways overwhelmingly favour forest to non-forest conversions, producing a landscape increasingly dominated by ecosystems with lower per-hectare service values and reduced resilience. Although total ecosystem function values associated with shrubland and grassland increase, these gains are insufficient to offset the magnitude and quality of forest-based losses, particularly in regulating and supporting services that underpin long-term socio-ecological stability.

At the aggregate level, the DIS scenario results in a net and structurally irreversible decline in ecosystem functionality, characterised by the erosion of high-value services and the proliferation of low-value substitutes. Unlike BAU, where functional degradation occurs gradually, DIS accelerates ecosystem service loss and compresses it into a shorter temporal window. This confirms that development-intensive pathways do not merely shift ecosystem services spatially, but actively degrade the functional capacity of the landscape. In hypothesis terms, H_{1a} and H_{1b} are strongly validated by the scale of absolute and proportional EF losses,

while H_{2a} and H_{2b} are confirmed by the class-specific sensitivity of forest systems and the fundamentally altered functional structure of the LULC system.

Generally, the DIS ecosystem-function results depict a trajectory of rapid functional collapse rather than incremental erosion. Accelerated development leads to severe reductions in climate regulation, biodiversity support, and ecological buffering capacity, increasing long-term environmental risk in a peri-urban reserve context. These findings position DIS as the most ecologically costly pathway among the evaluated scenarios and provide a stark contrast to the functional recovery observed under conservation-oriented management. The results therefore underscore the central conclusion of the study: development without effective spatial and environmental governance imposes substantial and quantifiable ecosystem-function losses that undermine both sustainability and long-term development objectives.

Table 13: Ecosystem function values of major LULC classes in Kazimzumbwi Forest Reserve under the Development-Intensive Scenario (DIS), 2024–2054

LULC	Ecosystem services	Local EF (Million US$)			Global EF (Million US$)		
		2024	2054	Relative change	2024	2054	Relative change
Closed forest	Provisioning services	0.12	0.03	−70.6	0.35	0.10	−70.6
	Regulating services	0.56	0.16	−70.6	1.00	0.29	−70.6
	Supporting services	0.19	0.06	−70.6	0.83	0.24	−70.6
	Cultural services	0.01	0.00	−70.6	0.10	0.03	−70.6
	Sub-total	0.88	0.26	−70.6	1.78	0.53	−70.6
Open woodland	Provisioning services	0.18	0.12	−31.6	0.55	0.38	−31.6
	Regulating services	0.87	0.60	−31.6	1.57	1.07	−31.6
	Supporting services	0.30	0.20	−31.6	1.30	0.89	−31.6
	Cultural services	0.01	0.01	−31.6	0.16	0.11	−31.6
	Sub-total	1.37	0.94	−31.6	2.79	1.91	−31.6
Shrubs	Provisioning services	0.15	0.18	+21.5	0.46	0.56	+21.5
	Regulating services	0.73	0.89	+21.5	1.36	1.65	+21.5
	Supporting services	0.25	0.30	+21.5	1.08	1.31	+21.5
	Cultural services	0.01	0.01	+21.5	0.13	0.16	+21.5
	Sub-total	1.15	1.38	+21.5	2.33	2.82	+21.5
Grassland	Provisioning services	0.11	0.13	+21.0	0.16	0.20	+21.0
	Regulating services	0.14	0.17	+21.0	0.14	0.17	+21.0
	Supporting services	0.02	0.03	+21.0	0.02	0.03	+21.0
	Cultural services	0.00	0.00	+21.0	0.00	0.00	+21.0
	Sub-total	0.27	0.33	+21.0	0.32	0.39	+21.0

Comparative ecosystem-function outcomes under BAU, COS, and DIS scenarios in Kazimzumbwi Forest Reserve (2024–2054)

The comparative ecosystem-function outcomes across the Business-as-Usual (BAU), Conservation-Oriented Scenario (COS), and Development-Intensive Scenario (DIS) provide a synthetic and policy-relevant assessment of how alternative land-use trajectories translate into functional gains or losses in Kazimzumbwi Forest Reserve (KFR) over the 2024–2054 period as indicated in Tables 14a & 14b. By aggregating local and global ecosystem function (EF) values, the results move beyond class-specific analyses to reveal scenario-level patterns that directly address the study hypotheses (H_{1a}, H_{1b}, H_{2a}, and H_{2b}) and clarify the broader socio-ecological implications of competing development and conservation pathways.

Under the BAU scenario, total ecosystem-function values exhibit a modest but consistent decline, with local EF decreasing by 2.7% (from US$3.67 million to US$3.57 million) and global EF declining by 3.0% (from US$7.22 million to US$7.00 million). Although the magnitude of loss appears relatively small in aggregate terms, the underlying driver is structurally significant: gradual degradation of forest systems is only partially offset by expansion of open woodland and grassland. This pattern confirms that BAU represents a trajectory of incremental functional erosion rather than stability. In hypothesis terms, these outcomes support H_{1a} and H_{1b} by demonstrating measurable absolute and proportional ecosystem-function change over time, even in the absence of rapid deforestation. The BAU scenario thus reinforces the notion that continuation of existing trends leads to cumulative losses in high-value ecosystem services, particularly those linked to forest regulation and support functions.

In contrast, the COS scenario is the only pathway that yields a positive net ecosystem-function balance. Total local EF increases by 5.2% (from US$3.67 million to US$3.86 million), while global EF rises by 5.4% (from US$7.22 million to US$7.61 million). These gains are driven overwhelmingly by recovery and stabilization of forest systems, which enhance regulating and supporting services such as climate regulation, carbon sequestration, erosion control, and habitat provision. The positive net change under COS provides strong confirmation of H_{1a} and H_{1b}, demonstrating that alternative policy pathways can produce not only different magnitudes but also opposite directions of ecosystem-function change. Moreover, the COS outcome substantiates H_{2a} by showing that forest systems respond disproportionately to conservation-oriented governance, delivering functional gains that exceed those achievable through secondary vegetation alone.

The DIS scenario presents a stark contrast, with ecosystem-function losses that are both large and rapid. Total local EF declines by 20.7% (from US$3.67 million to US$2.91 million), while global EF contracts by 21.7% (from US$7.22 million to US$5.65 million). These losses are an order of magnitude greater than those observed under BAU and reflect large-scale forest loss combined with the suppression of regeneration pathways. The magnitude of decline under DIS provides unequivocal support for H_{1a} and H_{1b}, confirming that development-intensive trajectories generate the largest absolute and proportional ecosystem-function losses among all scenarios. Importantly, the severity of loss at both local and global scales underscores that development-driven land conversion undermines ecosystem services with both local livelihood relevance and global environmental significance

Disaggregation by major LULC groups further clarifies the mechanisms underlying these scenario-level outcomes. Forest systems (closed forest and open woodland) experience net ecosystem-function losses under BAU (−US$0.12 million) and DIS (−US$1.08 million), but show a substantial gain under COS (+US$0.22 million). This pattern provides strong empirical support for H_{2a}, confirming that forest-based ecosystems are the most sensitive and influential contributors to overall ecosystem-function trajectories. The results also validate H_{2b} by demonstrating that scenario-specific transition dynamics fundamentally reshape the internal functional structure of the landscape: forest persistence and regeneration under COS generate positive feedbacks, whereas forest-to-non-forest transitions under DIS drive irreversible functional decline.

Secondary vegetation (shrubland and grassland) shows a contrasting pattern. Under BAU and especially DIS, gains in secondary vegetation EF are observed (+US$0.04 million and +US$0.29 million, respectively), whereas COS produces a slight decline (−US$0.05 million) as these classes contract in favour of forest recovery. Crucially, however, the gains observed under DIS do not compensate for forest losses in functional terms. Instead, they represent low-value substitutes dominated by provisioning services and limited regulating capacity. This reinforces the conclusion that ecosystem-function outcomes are shaped not only by total area but by the quality and composition of land-cover classes, further substantiating H_{2b}.

Altogether, the comparative results demonstrate that ecosystem-function trajectories in KFR are highly contingent on land-use governance choices rather than inevitable outcomes of urbanisation or population growth. BAU leads to a slight but persistent net loss of ecosystem functions, COS delivers a clear functional gain through forest recovery, and DIS results in severe and rapid functional collapse. In hypothesis terms, all four hypotheses are strongly supported: H_{1a} and H_{1b} by the significant divergence in absolute and proportional ecosystem-function outcomes across scenarios, and H_{2a} and H_{2b} by the class-specific sensitivity and scenario-dependent restructuring of ecosystem functions. Thus, the integrated comparison establishes that only the Conservation-Oriented Scenario produces a positive ecosystem-function balance, confirming that conservation and restoration are not merely protective strategies but active drivers of functional enhancement. Conversely, development-intensive pathways impose substantial opportunity costs through lost ecosystem services that cannot be offset by expansion of lower-value land-cover types. These findings provide a robust functional justification for prioritising conservation-oriented land-use strategies in peri-urban forest reserves such as KFR, where the trade-offs between development and ecosystem sustainability are particularly acute.

Table 14a: Comparative ecosystem-function outcomes under BAU, COS, and DIS scenarios in Kazimzumbwi Forest Reserve (2024–2054)

Scenario	Total Local EF (2024)	Total Local EF (2054)	Net Change	% Change	Total Global EF (2024)	Total Global EF (2054)	Net Change	% Change
BAU	3.67	3.57	−0.10	−2.7	7.22	7.00	−0.22	−3.0
COS	3.67	3.86	+0.19	+5.2	7.22	7.61	+0.39	+5.4
DIS	3.67	2.91	−0.76	−20.7	7.22	5.65	−1.57	−21.7

Note. Values in Million US$ per year; 1994 constant prices

Table 14b: Ecosystem-function losses and gains by major LULC group (2054 vs 2024)

LULC Group	BAU	COS	DIS
Forest systems (CF + OW)	−0.12	+0.22	−1.08
Secondary vegetation (SH + GL)	+0.04	−0.05	+0.29
Net ecosystem outcome	Slight loss	Net gain	Severe loss

Note. Values in Million US$ per year; 1994 constant prices

Discussions

Forecasted changes in the economic values of ecosystem services (ESV) resulting from LULC dynamics in Kazimzumbwi Forest Reserve (2024–2054)

The scenario-based assessment of ecosystem service values (ESV) demonstrates that future economic outcomes in Kazimzumbwi Forest Reserve (KFR) are highly contingent on land-use and land-cover (LULC) pathways, thereby confirming the central premise of this study. Across the Business-as-Usual (BAU), Conservation-Oriented Scenario (COS), and Development-Intensive Scenario (DIS), both absolute and proportional changes in ESV diverge markedly, providing strong empirical support for hypotheses H_{1a} and H_{1b}, which posited significant scenario-dependent differences in ecosystem service outcomes.

Under the BAU scenario, total local and global ESV exhibit modest net declines by 2054. Although the aggregate reduction appears relatively small, this masks a substantive internal reallocation of ecosystem services. High-value regulating and supporting services associated with closed forest decline substantially, while lower-value services linked to open woodland and grassland expand. This compositional shift confirms that incremental forest degradation can erode ecosystem value even when total ESV losses appear limited. Such "slow erosion" dynamics are widely reported in peri-urban forest systems where land-use pressures accumulate in the absence of strengthened governance, leading to gradual but persistent declines in ecosystem service quality Nkinda et al., 2025; Eibedingil, 2024). In hypothesis terms, BAU validates H_{2a} by demonstrating the disproportionate sensitivity of forest classes to land-use change and H_{2b} by showing that unchanged transition probabilities favour degradation pathways over regeneration.

In contrast, the COS produces a positive economic trajectory, with both local and global ESV increasing by more than 5% over the study period. These gains are driven primarily by recovery and stabilization of closed forest, which yields high per-hectare values for regulating and supporting services such as climate regulation, erosion control, nutrient cycling, and habitat provision. Open woodland remains largely stable, while shrubland and grassland contract slightly as ecological succession favours forest regeneration. This pattern demonstrates that conservation-oriented governance not only prevents loss but generates net economic benefits from ecosystem services, directly supporting hypotheses H_{1a} and H_{1b}. The COS findings align with scenario-based studies across East Africa and other tropical regions showing that restoration and protection produce disproportionate returns in ecosystem value relative to the area restored (Soares-Filho et al., 2002; Liu et al., 2025; Yu et al., 2025).

The DIS represents the most adverse economic outcome, with total ESV declining by more than 20% by 2054. Losses are concentrated in closed forest and open woodland, whose conversion sharply reduces regulating and supporting services that underpin both local livelihoods and global public goods. Although shrubland and grassland expand and contribute modest gains in provisioning services, these increases are insufficient to offset the large losses

incurred through forest degradation. This substitution effect illustrates a critical non-linearity in ecosystem economics: expansion of low-value land covers cannot compensate for the loss of high-value forest systems. The DIS outcomes provide strong confirmation of hypotheses H_{1a} and H_{1b}, and echo findings from rapidly urbanising landscapes where development-driven LULC change leads to significant declines in ecosystem service values and heightened socio-ecological vulnerability (Lin et al., 2024; Montanarella, 2018).

Comparatively, the cross-scenario ESV analysis underscores that COS is the only pathway delivering a positive net ecosystem-service balance, BAU results in incremental but consequential losses, and DIS drives rapid and economically significant degradation. These contrasts reinforce the conclusion that ecosystem service trajectories in KFR are not inevitable outcomes of urbanisation but rather the product of policy choices and land-use governance, consistent with broader land-system science literature (Pontius et al., 2025; Turner et al., 2007).

Forecasted changes of ecosystem-function values of Kazimzumbwi Forest Reserve from 2024 to 2054

Beyond monetary valuation, analysis of ecosystem-function values provides insight into the biophysical processes underlying observed economic trends. Across scenarios, changes in regulating, supporting, provisioning, and cultural functions closely mirror LULC dynamics, offering strong validation of hypotheses H_{2a} and H_{2b}, which anticipated differential functional responses and scenario-specific transition behaviours.

Under BAU, ecosystem functioning progressively shifts away from high-complexity forest systems toward simpler secondary vegetation. Losses in regulating functions—particularly climate regulation, erosion control, and hydrological regulation—are only partially offset by modest gains in provisioning services from open woodland and grassland. Supporting functions such as nutrient cycling and habitat provision also decline as forest persistence probabilities fall. This functional downgrading reflects path-dependent dynamics typical of peri-urban landscapes under weak enforcement, where ecosystems transition toward lower-resilience states (Yu et al., 2025; Turner et al., 2007).

The COS fundamentally alters these dynamics by enhancing forest persistence and regeneration. Increases in ecosystem-function values are concentrated in regulating and supporting services, reflecting recovery of carbon sequestration capacity, improved soil stability, enhanced water regulation, and strengthened habitat connectivity. These gains demonstrate that conservation and restoration interventions generate multiplicative functional benefits that extend beyond the reserve boundary, reinforcing urban resilience and climate mitigation objectives. Similar outcomes have been reported in restoration-focused scenario studies, which consistently show that forest recovery yields non-linear improvements in ecosystem functioning relative to area restored (Soares-Filho et al., 2002; Liu et al., 2025).

In stark contrast, DIS leads to a collapse of ecosystem functioning. Accelerated forest conversion suppresses regeneration pathways, resulting in sharp declines in regulating and supporting functions that are only marginally compensated by increases in low-resilience provisioning services associated with shrubland and grassland. The resulting ecosystem-function profile is dominated by land covers with limited capacity to buffer climate extremes, regulate hydrology, or sustain biodiversity. Empirical studies from other rapidly developing regions similarly show that such trajectories increase exposure to floods, heat stress, and water scarcity, ultimately undermining the sustainability of development gains (Lin et al., 2024; Montanarella, 2018).

Synthesized across scenarios, ecosystem-function outcomes strongly support hypothesis H_{2a}, as forest-related classes emerge as the primary determinants of functional change, and hypothesis H_{2b}, as scenario-specific transition probabilities produce fundamentally different functional configurations. COS restructures the system toward high-value, resilient functions; BAU allows gradual erosion of functional complexity; and DIS pushes the landscape toward a degraded, low-functioning state. Collectively, these findings demonstrate that safeguarding and restoring forest systems within KFR is essential not only for maintaining ecosystem service values but also for preserving the underlying ecological functions that support long-term socio-economic resilience in rapidly urbanising peri-urban environments.

Conclusion and Recommendations

Conclusion

This study set out to evaluate how alternative land use and land cover (LULC) trajectories would shape future ecosystem services and ecosystem functioning in Kazimzumbwi Forest Reserve (KFR) over the 2024–2054 period. By integrating scenario-based LULC forecasting with ecosystem service valuation and functional analysis, the study provides robust, forward-looking evidence on the consequences of land-use decisions in a rapidly urbanising peri-urban forest landscape. The findings demonstrate unequivocally that future ecological and economic outcomes in KFR are not predetermined, but are instead highly contingent on policy orientation, governance effectiveness, and land-use management choices.

Under the Business-as-Usual (BAU) scenario, the reserve experiences gradual but persistent degradation. While total ecosystem service values (ESV) decline only modestly in aggregate, this masks a critical internal shift from high-value forest-based regulating and supporting services towards lower-value provisioning services associated with secondary vegetation. This “slow erosion” trajectory confirms that maintaining current practices is insufficient to safeguard ecosystem integrity, and it validates the study’s hypotheses by showing that forest systems are disproportionately sensitive to incremental land-use pressures. BAU therefore represents a pathway of cumulative ecological risk, where small annual losses compound into significant long-term functional decline.

The Conservation-Oriented Scenario (COS) presents a fundamentally different future. Strengthened forest protection and active restoration reverse negative trends, resulting in net gains in both local and global ecosystem service values and substantial improvements in ecosystem functioning. Forest recovery enhances regulating and supporting services critical for climate regulation, biodiversity conservation, soil stability, and hydrological buffering. These outcomes provide strong empirical support for the hypothesis that conservation-focused governance can restructure land-use dynamics toward resilience and long-term value creation. COS emerges as the only scenario capable of delivering positive ecological and economic outcomes while accommodating surrounding urban growth.

In contrast, the Development-Intensive Scenario (DIS) produces severe and rapid ecosystem degradation. Extensive forest loss leads to large declines in ecosystem service values and a collapse of key ecosystem functions, with gains in shrubland and grassland unable to compensate for the loss of high-value forest services. This scenario confirms the hypothesis that development-driven land-use pathways generate the largest absolute and proportional ecosystem losses and fundamentally alter transition dynamics toward irreversible degradation. DIS highlights the long-term costs of short-term development gains, demonstrating that unchecked expansion undermines the natural capital upon which sustainable development depends.

Thereof, the study confirms all four hypotheses. Absolute and proportional ecosystem service outcomes differ significantly across scenarios; forest and non-forest classes respond differentially to land-use change; and scenario-specific transition probabilities generate distinct ecosystem service and functional configurations. The results underscore the central role of forest ecosystems in sustaining both local livelihoods and global public goods and demonstrate that conservation-oriented pathways offer the only viable route for maintaining and enhancing ecosystem services in peri-urban forest reserves such as KFR.

Recommendations

The findings of this study underscore the need for a deliberate shift toward conservation-oriented land-use governance in Kazimzumbwi Forest Reserve (KFR) and comparable peri-urban forest landscapes. First, national and local authorities should prioritise conservation-oriented land-use pathways as the default planning framework for KFR. This requires strengthening enforcement of existing forest protection regulations, clarifying and physically demarcating reserve boundaries, and reducing institutional ambiguity that enables incremental encroachment. Without firm regulatory commitment, even modest development pressures are likely to translate into cumulative forest degradation and long-term ecosystem service losses.

Second, forest restoration and regeneration initiatives should be scaled up, particularly in degraded zones with high ecological recovery potential. Assisted natural regeneration and targeted restoration of closed forest patches can yield disproportionately high returns in regulating and supporting ecosystem services, including carbon sequestration, soil stabilisation, and hydrological regulation. Prioritising these interventions is especially important in peri-urban contexts, where restored forests can function as natural infrastructure that enhances climate resilience for adjacent urban areas.

Third, ecosystem service valuation should be systematically integrated into land-use planning and decision-making processes. Embedding ecosystem service values within spatial planning frameworks, environmental impact assessments, and development approval procedures would allow decision-makers to explicitly account for the long-term ecological and economic costs of land conversion. Such integration would help avoid false trade-offs in which short-term development gains are pursued at the expense of irreplaceable ecosystem functions and services.

Fourth, management of KFR should be explicitly aligned with national and international policy commitments, including Tanzania's Nationally Determined Contribution (NDC), REDD+ strategy, AFR100 restoration targets, and long-term development visions. Peri-urban forest reserves represent high-leverage landscapes where conservation and restoration can contribute simultaneously to climate mitigation, biodiversity conservation, and sustainable development goals. Aligning reserve management with these frameworks can improve access to climate finance and enhance policy coherence across governance levels.

Fifth, inter-sectoral coordination and governance mechanisms must be strengthened. Effective management of peri-urban forests requires close collaboration among forestry, urban planning, infrastructure, environmental management, and local government institutions. Integrated planning platforms should be established to ensure that development policies, infrastructure expansion, and settlement planning do not undermine conservation objectives or compromise ecosystem service provision.

Sixth, sustained investment in monitoring, data integration, and scenario-based planning is essential for adaptive management. Continuous monitoring of LULC dynamics using remote sensing and geospatial technologies should be institutionalised to provide timely evidence for

decision-making. Scenario-based modelling, as applied in this study, should be routinely employed to evaluate the long-term consequences of alternative land-use policies before they are implemented, thereby reducing uncertainty and policy risk.

Seventh, community engagement and the promotion of sustainable livelihoods should be central to conservation efforts in KFR. Local communities must be actively involved in forest management through participatory governance arrangements that recognise their interests and knowledge. Supporting alternative livelihood options such as agroforestry, sustainable fuelwood systems, and nature-based enterprises can reduce dependence on forest exploitation while increasing local support for conservation-oriented policies.

Finally, future research and model refinement should be encouraged to strengthen the evidence base for land-use governance. Integrating dynamic climate projections, hydrological modelling, and socio-economic scenarios would enhance the accuracy and policy relevance of ecosystem service estimates. In addition, participatory scenario development involving stakeholders could improve the legitimacy, transparency, and applicability of future modelling exercises.

Thus, these recommendations highlight that proactive, conservation-oriented land-use governance is not only ecologically necessary but also economically rational. Decisions made today regarding the management of Kazimzumbwi Forest Reserve will shape ecosystem service provision, climate resilience, and sustainable urban development for decades to come. Implementing the measures outlined above can help ensure that KFR remains a functional, resilient, and valuable natural asset for both present and future generations.

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