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Wetland and Forest Restoration Enhances Multiple Ecosystem Service Recoveries and Resilient Livelihoods in the Tropics

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Abstract

The degradation of wetlands and forests is still a threat to the supply and recovery of ecosystem services in the tropics. Studies comparing restoration measures and ecosystem service recoveries are fragmented. This study investigated the spatial extent and drivers of wetland/forest degradation, and assessed the effects of restoration measures on the recovery of ecosystem services and resilient livelihoods. A cross-sectional household survey was conducted targeting households adjacent to restored and unrestored wetland/forest ecosystems. The data was analyzed using a Binary Logistic regression to characterize earlier and recovered ecosystem services between forest and wetland ecosystems. High spatial-resolution optical satellite imagery from the Airbus constellation was obtained and analyzed to examine wetland and forest degradation. Our findings revealed that the spatial extent of degraded land under wetlands and forests decreased between 2023 and 2025. Ecosystem service degradation was primarily driven by chronic poverty, excessive water abstraction, population growth, burning practices, overharvesting of resources, overgrazing, cultivation, infrastructure development, and the invasion of alien species ($p < 0.05$). The counteractive ecosystem restoration activities undertaken included mobilization and sensitization of communities on wetland restoration, wetland demarcation, revegetation, establishment of flood control measures, and provision of alternative livelihoods ($p \leq 0.05$). The multiple direct and indirect ecosystem service recoveries reported were provisioning services (increases in pasture, enhanced livestock production, increased soil productivity, health-related benefits from crops and livestock products) and regulating services (improved water quality/quantity). The ecosystem service recoveries were more significant in the restored wetlands than the forests. The indicators of enhanced ecosystem-based resilient livelihoods included increased household incomes, higher livestock yields, increased crop productivity, improved health from crop/livestock products, improved water quality/quantity, and enhanced scenic beauty and tourism ($p < 0.05$). The restoration activities in degraded wetland systems had more potential to facilitate full recovery of the wetland ecosystem compared to the absence of interventions. This evidence highlights the need to restore high-ecological-sensitive ecosystems to sustain the delivery of ecosystem services for community and environmental resilience.

Keywords: wetland; forest; degradation; ecosystems services; restoration; Uganda

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1. Introduction

Wetlands and forest ecosystems constitute the living backbone of the tropical landscape, covering millions of hectares. These ecosystems extend into the environment through their soils, waterways, and vegetation, sustaining both wildlife and human livelihood. Globally, forests cover approximately 41 million km^2, while wetlands span another 12.1 million km^2 [1,2], harboring a distinct share of the world's plant and animal species and storing vast reservoirs of carbon. These natural ecosystems function through quiet ecosystem elements, including rooted vegetation that stabilizes soils, water that filters through wetland beds, nutrient cycles that nourish living organisms, and habitat corridors that support wildlife movement [3,4]. When these elements interact harmoniously, they create landscapes that are capable of absorbing disturbances and regenerating after stress [5]. However, over the last century, wetland ecosystems have experienced severe global degradation, with about 87% of wetlands and 2000 million hectares of forests lost since the 1700s [6]. This decline is more pronounced in the United States, Europe, and China [7], driven by both natural factors, such as climate variability, and human activities, including deforestation, agriculture, urbanization, and resource overexploitation [8,9]

Over generations, many households across the tropics have relied on the steady flow of ecosystem services provided by wetlands and forests. It is evident that a family's water for farming and drinking often comes from wetland springs; daily cooking depends on fuelwood collected and gathered from forest edges; and food, fodder, medicinal plants, and non-timber products support local livelihoods [10,11]. At a broader scale, wetlands protect communities from floods, forests usually cool the environment, and together these ecosystems store carbon, acting as natural shields against the unfolding climate crisis [12,13]. However, increasing pressure from land use, resource extraction, and infrastructure development is causing declines in these services, weakening the resilience of the communities that rely on them [13,14].

The problem is particularly severe in tropical mountainous regions, including the Elgon and Rwenzori ranges, where steep slopes, intense rainfall, and human activity accelerate soil erosion, landslides, and river siltation [15,16]. Globally, tropical forests experienced an average annual forest loss of approximately 3.94 million hectares between 2010 and 2020, while African wetlands shrank at 2–4% per year [17]. Loss of ecological balance in these landscapes exposes communities to floods, unpredictable water flows, declining soil fertility, and reduced access to natural resources that once supported their livelihoods [18,19].

Recognizing these growing risks, national and subnational governments have resorted to ecological restoration to reverse degradation and rebuild resilience [20,21]. The government of Uganda is committed to restoring approximately 2.5 million hectares by 2030 under the AFR100 initiative, through firm policy and regulatory bodies, including the National Environment Management Authority, the National Environment Act, and the National Wetlands Policy [21]. Local governments and districts are also implementing restoration programs, such as demarcating wetland and forest boundaries, regenerating forests, stabilizing riverbanks, and partnering with local communities to reduce pressure on these fragile natural ecosystems [22,23]. These interventions reflect the understanding that wetland and forest restoration benefits both the environment and local communities [24,25].

Within Uganda's restoration efforts, Sironko and Ibanda Districts reflect both the challenges and opportunities of tropical ecosystem restoration. The ever-increasing population of Sironko is a threat to wetlands and forests, driven by the search for farmland, space for settlement, and sand for construction. This expansion has altered the River Sironko corridor, reducing water retention and increasing erosion [26]. In Ibanda, wetland and forest degradation is driven by agriculture, sand mining, brick laying, and craft production [27]. Through government support and community mobilization, degraded wetland sections are being demarcated and replanted, forest patches are regenerating, and alternative livelihood initiatives are reducing human pressure on these fragile landscapes [28].

Whereas several studies have profiled the causes of environmental degradation and the loss of ecosystem services, and their implications for human well-being [29,30], there remains a critical knowledge gap regarding how communities perceive the drivers of forest and wetland degradation in the tropics and the contributions of restoration interventions. Little emphasis has been placed on the qualification of restoration measures in wetland and forest ecosystems in the tropics, particularly understanding the extent of degradation, recovery, and resupply of ecosystem services. Furthermore, a comparative analysis of ecosystem supply recoveries between these two ecosystems is also inadequate. Secondly, although wetland and forest degradation have been widely documented, this threat to community forests and permanent wetlands has received little attention; this study brings it to the attention of conservation planners. Thirdly, despite the introduction of restoration interventions in wetlands and forests in the global south, this study argues that the promotion of alternative livelihoods should be prioritized, particularly for affected households, to sustain the measures implemented to facilitate the recovery of these ecosystems from the scars of degradation.

This study addressed these knowledge gaps by applying an integrative approach to investigate community perceptions of the causes of degradation in forest and wetland ecosystems and the recovery of ecosystem services following restoration interventions in the Sironko and Ibanda districts, located in Eastern and Western Uganda, respectively. The districts are characterized by diverse forest and wetland ecosystems that are threatened by population pressures associated with settlement and agricultural land expansion. The communities, however, have been mobilized to undertake interventions to restore degraded patches of these ecosystems. As such, the paper's research questions were as follows:

1. What are the extent and drivers of wetland/forest degradation before and after restoration?
2. What are the effects of wetland/forest restoration on the supply of ecosystem services?
3. Are there any statistical differences in the supply of ecosystem services between the restored and unrestored wetland/forest sites?
4. Are there any statistical differences in the recovery of ecosystem services between the restored wetland and forest ecosystems?

This study aims to provide evidence on the importance of restoring degraded wetland and forest ecosystems, raise awareness about the need to conserve fragile ecosystems, support increased budgetary allocations for natural resource management, and strengthen the integration of ecosystem service supply into climate adaptation planning in rural communities.

2. Materials and Methods

2.1. Description of the Study Area

This study was conducted in two districts: Sironko (Eastern) and Ibanda (Western) (Figure 1). These districts were selected based on their ecological sensitivity (adjacent mountainous ecosystems—Mt Elgon and Rwenzori—and the presence of Rivers—Sironko and Mpanga in Ibanda); widespread wetland and forest ecosystem degradation; and proneness to the devastating impacts of flash floods and prolonged droughts. In Sironko district, rainfall ranges from 2000 to 3000 mm annually in the wetter upper areas near Mt. Elgon to about 1000 mm in the downstream areas [31]. These range from 27 °C to 32 °C mean maximum temperatures and from 15 °C to 17 °C mean minimum temperatures in the lowlands. In highland areas, mean maximum temperatures range from 25 °C to 28 °C, and mean minimum temperatures range from 15 °C to 16 °C [32]. The soil composition varies considerably across the landscape, comprising laterites, sandy loams, and volcanic

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soils [32]. The soils consist mainly of volcanic ash decomposition products, forming clay soils in shades of red, black, or gray, mixed with sand- and gravel-sized particles.

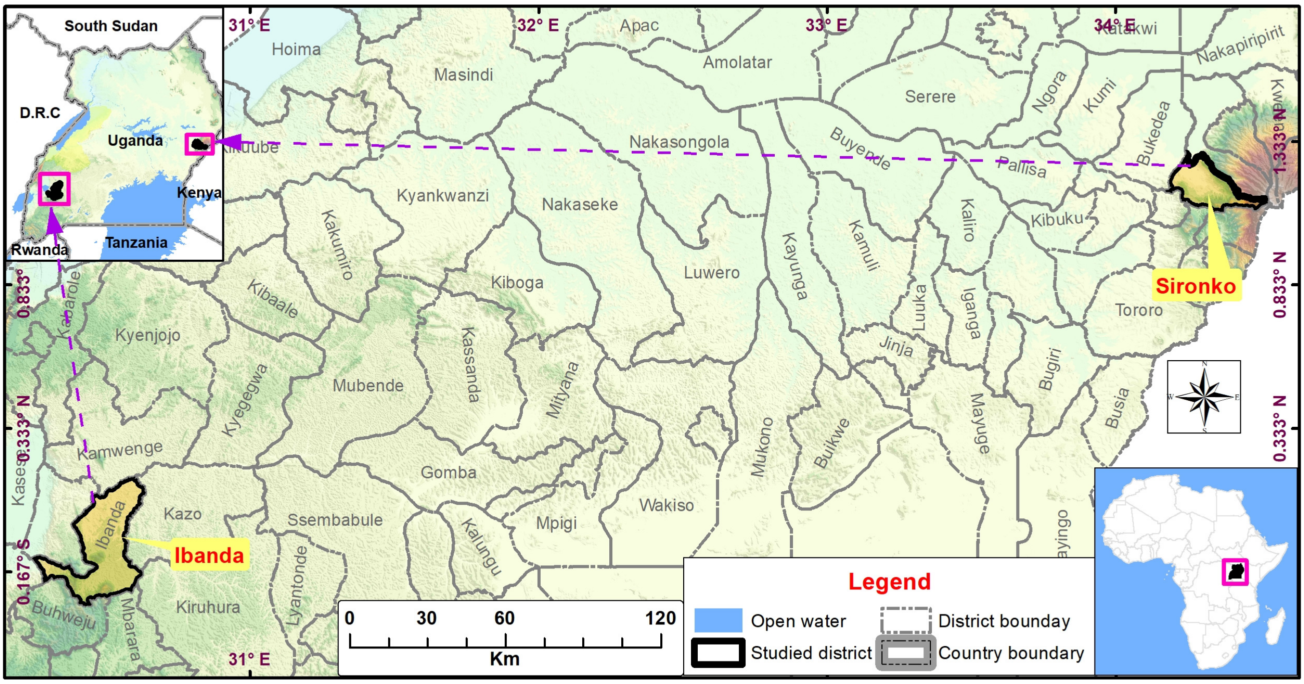

Figure 1. Location of the studied districts (Ibanda and Sironko) and an inset map showing the districts' locations in Uganda (Purple square).

On the other hand, Ibanda District lies at elevations ranging from 1800 to 13,000 m above sea level. The district experiences a tropical climate, hot and wet, with an average annual rainfall of 1000–1200 mm. There are two rainy seasons, from mid-August to December and from mid-March to mid-May, with a short dry spell between them, lasting from mid-June to mid-July, and a long dry spell from late November to early March. These modifications have contributed to unexpected heavy rains and, at times, long dry spells. District temperatures range from 12.5 °C to 30 °C, with extremes recorded in February. The soils are predominantly derived from weathered pre-Cambrian basement rocks, including gneiss and granitoids, resulting in a variety of soil types influenced by topography and climate. The upland areas are mainly covered by Ferralsols and Nitisols, which are deep red, well-drained, clay-rich, but generally acidic and nutrient-poor due to intense weathering [33].

2.2. Analysis of Wetland Degradation

Wetland use/cover (structural) changes were used as an indicator of wetland degradation. High-resolution optical satellite imagery from the Airbus constellation was acquired for all sites. To ensure consistency in analysis, images with minimal cloud cover (<20%) and comparable conditions across seasons were selected. The images were all pre-processed in Google Earth Pro (version 7.3.6.10441), using ground truth points (34) to georeference and rectify the imagery. Tilting corrections were applied before downloading to minimize geometric distortion. Ecosystem boundaries were overlaid using a wetland shapefile (2022) provided by the Ministry of Water and Environment (MWE). The boundaries were refined by comparing field survey data with historical satellite imagery and by visual inspection (Table 1).

Table 1. Temporal and spatial attributes of satellite images that were used in the baseline assessment.

Ecosystem	District	Type	Date of Acquisition		Satellite	Resolution (m)
			2023	2025		
Rwambu wetland	Ibanda	Restored	11 March 2021	30 October 2024	Airbus	0.301
Kafunjo forest	Ibanda	Restored	7 April 2020	16 January 2025	Airbus	0.371
Mutufu forest	Sironko	Restored	15 May 2023	20 January 2025	Airbus	0.377
Mutufu wetland	Sironko	Restored	7 July 2022	20 January 2025	Airbus	0.345

Supervised classification was conducted using the Maximum Likelihood Classification (MLC) algorithm, a probabilistic approach widely recognized for its accuracy in remote sensing. Representative training samples for each wetland use/cover class were identified using Google Earth Pro and field validation points. The classification was implemented in QGIS (version 3.38) and ArcGIS (version 10.8.2) platforms. An error matrix methodology was used to estimate overall image classification accuracies: Rwambu (92%), Kafunjo (92%), Mutufu wetland (91%), and Mutufu forest (93%). Refer to the Supplementary Materials for tables on image classification accuracy assessment. Reclassification was performed to organize the spectral classes into seven classes based on the physical attributes of features observed in satellite images and field validation data (Table 2).

Table 2. Description of wetland use/cover types that were mapped in the assessment.

No	Class	Description
1	Built-up areas	Wetlands are converted into settlements, industries, roads, and other developments.
2	Cropland	These are wetlands under cultivation for both subsistence and commercial purposes.
3	Grassland	These are wetlands with tall and short grasses, scattered tall trees, shrubs, and palm trees with grasslands underneath.
4	Papyrus	These are wetlands with rooted and floating vegetation that can grow up to 5–6 m
5	Open water	These are areas covered with natural water, dams, and ponds
6	Tree cover	These are wetlands that have been converted into tree plantations, such as eucalyptus and pine.
7	Impediment	Bare rocks

2.3. Household Population and Sampling

The population in the current cross-sectional survey comprised households adjacent to forest and wetland ecosystems in the Sironko and Ibanda districts. The districts are located in the Afromontane agroecological zone. The sampling design was developed to enable the collection of perceptions and experiences from communities in both restored and unrestored areas within the same ecosystem. The choice of restored and unrestored regions studied was purposively selected in consultation with district environmental officers and local leaders and informed by a review of restoration program records. The target households were interviewed upon informed consent to participate in the survey.

A stratified random sampling technique was used to select households from both restored and unrestored areas across the forest and wetland ecosystems. The entire area was divided into sub-counties and parishes, representing separate strata. Within each parish, villages surrounding the selected forest and wetland ecosystems were identified and listed.

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The survey included all villages within a 5 km radius of the forest and wetland ecosystems, since forests and wetlands may exert direct and indirect ecological and socio-economic effects within this range.

A total of 12 villages were selected for the wetland ecosystem (6 restored and 6 unrestored) and 15 for the forest ecosystem (8 restored and 7 unrestored), for a total of 27 villages, ensuring adequate representation of both restored and unrestored sites. The sample included villages with varying degrees of restoration intervention and ecological condition to capture a wide range of community experiences. The number of sampled households in each town was determined proportionally to the village's population relative to the total population of all selected villages: villages with larger populations contributed more households, thereby ensuring representativeness across communities surrounding the ecosystems.

The application of stratified sampling ensured a logical distribution across the selected sites, enabling the collection of proportionate and representative data that reflected the study area's diversity. In total, 275 households were surveyed from wetland ecosystem villages (177 in restored sites and 98 in unrestored sites), with 29 and 16 households selected from each village near restored and unrestored wetland ecosystems, respectively. On the other hand, 817 households were surveyed from forest ecosystem villages (719 in restored sites and 98 in unrestored sites), with 89 and 14 households selected from each village near restored and unrestored forest ecosystems, respectively. Households that reported interacting with both ecosystems were included in both categories to examine linkages among ecosystem service degradation, restoration interventions, and changes in household income.

The sample size determination procedure was used to determine the required sample size from the study population surrounding forest and wetland ecosystems. The Krejcie and Morgan method helps estimate sample size when the population size is known [34]. It is ideal for determining statistically appropriate sample sizes in research surveys, just like the present study. The application of stratified sampling ensured a logical distribution across the selected sites, enabling the collection of proportionate and representative data that reflected the study area's diversity. The communities perceived improvements in ecosystem services relative to the resources harnessed over the last 10 years, when ecosystems were not widely encroached upon.

The selected wetland and forest ecosystems were studied due to their long-term ecological degradation and because restoration interventions (2022–2024) had commenced by the Ministry of Water and Environment (Figure 2). The period studied was sufficient to track the recovery of ecosystem services, given the similarity of climatic conditions of the assessed ecosystems. The households assessed improvements in ecosystem services by comparing levels between 2002 and 2024. Ecosystem service improvement indicators used to track changes included ecosystem quality and quantity, flood regulation, and ecosystem coverage. The points of departure were used to assess perceived recovery after restoration, using a Likert scale (1–5).

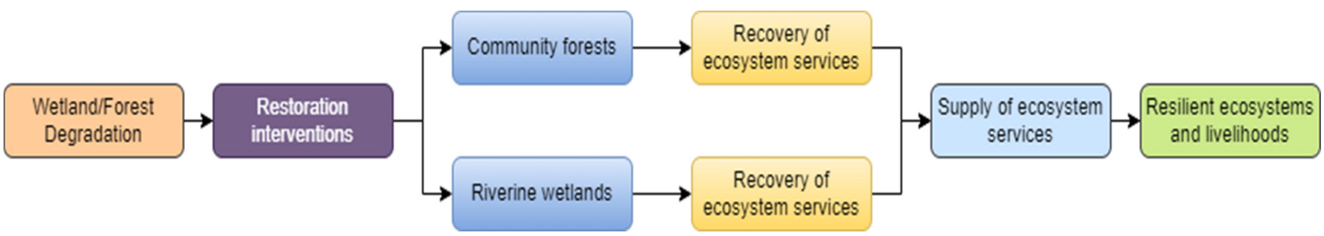

Figure 2. Conceptual framework of the study.

2.4. Data Collection

A semi-structured questionnaire was designed and administered to collect data on socio-demographic characteristics, perceptions of degradation and restoration activities, community participation, and changes in ecosystem services. The questionnaire was developed based on a review of validated frameworks and the existing literature in ecosystem restoration and rural livelihoods. The draft instrument was reviewed by environmental scientists, restoration practitioners, and researchers to ensure validity. A pilot study was conducted with a small sample of households in the forest and wetland ecosystems prior to fieldwork. Feedback from the pilot clarified and structured the research questions, making them more relevant. The questionnaire was then administered by the data collection team, comprising four trained research assistants in each ecosystem, all with experience in rural surveys and fluent in local languages. Data collection took place over 2 months. Although the initial target was 373 households, 33 individuals declined to participate, resulting in 340 completed interviews. Of these, 25 questionnaires were excluded due to excessive missing data; hence, 315 valid questionnaires were included in the analysis.

2.5. Data Analysis

The collected data were coded and entered into SPSS (Version 25) for analysis. Descriptive statistics, including frequencies and percentages, were first computed to summarize the distribution of ecosystem service indicators across restored and unrestored communities. A binary logistic regression analysis was employed to examine the effect of wetland/forest restoration on ecosystem services and their supply, and to compare recovery between restored and unrestored communities. The regression model was selected because the outcome variable for each ecosystem service indicator was binary (1 = service reported as present, 0 = service not reported), allowing estimation of the likelihood of service provision while controlling for potential confounding variables. The restored variable was coded as 1 for restored sites and 0 for unrestored communities. The ecosystem type was coded as 1 for wetlands and 0 for forests. Odds ratios and 95% confidence intervals were computed for each ecosystem service to assess whether the likelihood of service supply differed significantly between restored and unrestored communities and between wetlands and forests.

The estimated coefficients from the regression model are presented as Odds Ratios (OR), which measure how the odds of reporting a given ecosystem service change with a one-unit increase in a predictor (for binary predictors, the shift from 0 to 1).

Any Odds Ratio > 1 indicates a higher likelihood of service supply in the reference group (restored communities or wetlands); OR = 1 suggests no effect of restoration. In comparison, values OR < 1 indicate a higher likelihood in the comparison group (unrestored communities or forest ecosystem). For each OR, the study reported the 95% confidence interval (95% CI), which shows the range within which the actual OR would fall 95% of the time if data were repeatedly sampled from the same population. An OR was considered statistically significant at approximately the 0.05 level if its 95% CI did not include 1.

Statistical significance was assessed using p-values, which were reported for each OR. The results were considered statistically significant when $p < 0.05$. A small p-value indicates that the observed association is unlikely to be due to chance, suggesting a real effect.

The binary logistic regression model formula is expressed as

$$Logit(p(Y = 1)) = \beta_0 + \beta_1 Restoration + \beta_2 X_2 \ldots + \beta_n X_n \quad (1)$$

where

- P (Y = 1) is the probability that the ecosystem service is enhanced.

- Logit is the log-odds transformation. The logit link function maps linear predictors to probabilities bounded between 0 and 1. Placing the model on the log-odds scale allows a linear combination of predictors (βs) while ensuring that predicted probabilities remain in the valid range (0–1).
- Restoration is a binary variable (1 = restored, 0 = unrestored).
- X2, . . ., Xn are additional covariates.
- β1 is the coefficient indicating the effect of restoration on the likelihood of service enhancement. Additional covariates included household socio-demographic factors (household size, livelihood, level of education), distance to the ecosystem edge, participation in restoration, and site-level factors such as time since restoration started. To ensure model reliability, standard diagnostic checks were performed: multicollinearity was assessed using variance inflation factors (VIFs), model fit was evaluated using the Hosmer–Lemeshow goodness-of-fit test, and classification accuracy (sensitivity/specificity) and the Area Under the Curve (AUC) were computed. Sensitivity analyses (e.g., excluding observations with borderline missing values and alternative covariate sets) were performed to assess the robustness of the OR estimates.

3. Results

3.1. The Extent and Drivers of Wetland/Forest Degradation Before and After Restoration

3.1.1. Extent of Wetland/Forest Degradation Before and After Restoration

Rwambu wetland is a restored ecosystem-based adaptation (EbA) wetland located in Rwambu village, along the River Rwambu. In 2023, during the baseline wetland use/cover analysis, papyrus, tree cover, cropland, and grassland were the dominant wetland use/cover types, accounting for 29.2%, 26.5%, 24.1%, and 18.7%, respectively. Built-up areas occupied less than 1% of the total wetland area for the study periods. In 2025, the dominant wetland use/cover type occupied over 45% of the total wetland area, with gains of over 2 hectares each in cropland, tree cover, and grasslands (Table 3 and Figure 3). Croplands have declined by 17.7%, with land converted to grasslands. Grassland, despite losing to papyrus, increased by 3.31%, gaining approximately 2 hectares from papyrus in addition to other moderate gains from tree cover and cropland. Generally, an increase in grassland and papyrus cover indicates a gradually regenerating or restoring ecosystem, as also indicated by a reduction in built-up areas. A decrease in tree cover suggests a decline in tree plantations within the wetlands following restoration. This increases the wetland's potential as a water catchment area, controlling floods, increasing water retention, enriching biodiversity, moderating evapotranspiration, and regulating weather (Table 4).

Table 3. Wetland use/cover statistics for the Rwambu wetland between 2023 and 2025.

Wetland Use/Cover	**2023**		**2025**		**Change**	
	Area (ha)	**Area (%)**	**Area (ha)**	**Area (%)**	**Area (ha)**	**Area (%)**
Tree cover	4.67	26.56	4.21	23.96	−0.46	−2.60
Grassland	3.30	18.78	3.88	22.09	0.58	3.31
Built-up	0.08	0.44	0.06	0.35	−0.02	−0.09
Cropland	4.24	24.14	1.12	6.37	−3.12	−17.77
Papyrus	5.14	29.27	8.16	46.46	3.02	17.19
Open water	0.14	0.82	0.14	0.77	−0.01	−0.05

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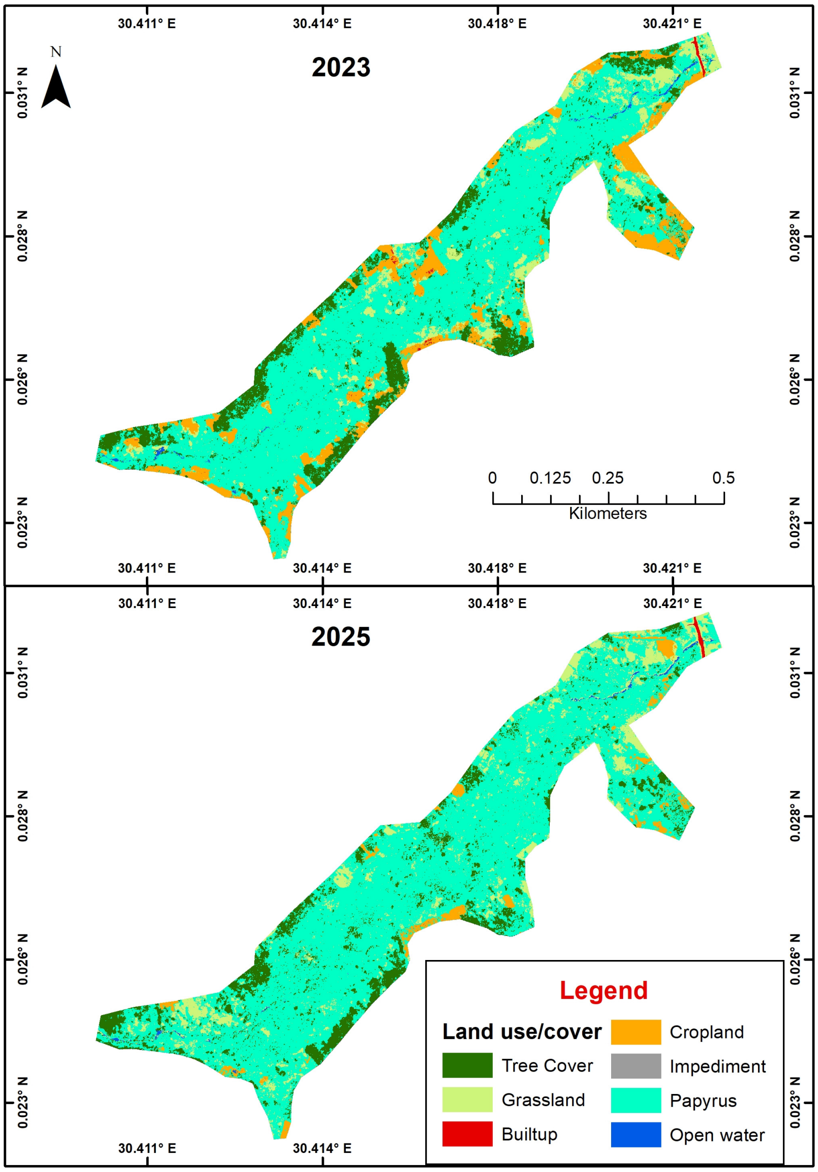

Figure 3. Wetland use/cover analysis for the Rwambu wetland ecosystem between 2023 and 2025.

Table 4. Transition analysis for the Rwambu wetland between 2023 and 2025.

	2023 (ha)							
	Wetland use/cover	Tree cover	Grassland	Built-up	Cropland	Papyrus	Open water	Total
2025	Tree cover	1.98	0.06	0.00	0.47	1.69	0.01	4.21
	Grassland	0.26	0.97	0.01	0.61	2.02	0.00	3.88
	Built-up	-	0.02	0.04	0.00	0.00	-	0.06
	Cropland	0.17	0.13	0.01	0.52	0.29	-	1.12
	Papyrus	2.25	2.12	0.02	2.64	1.14	0.00	8.16
	Open water	-	-	-	-	-	0.14	0.14
	Total	4.67	3.30	0.08	4.24	5.14	0.14	17.57

The Kafunjo forest ecosystem (Ibanda Saza Local Forest Reserve) is located in Kafunjo village, Kafunda Subcounty, Ibanda District, in western Uganda, within the River Mpanga catchment. The forest use/cover analysis of the Ibanda Saza Local Forest Reserve in 2023 revealed that grassland was the dominant forest cover type, occupying more than 60% of the landscape area. Tree cover occupied about 30% of the total land area, while croplands occupied less than 5% (Table 5 and Figure 4). In 2025, tree cover increased by more than 25% of the total area, mainly from grasslands (about 4.5 hectares), thereby nearly doubling total coverage, as evidenced by a similar loss in grassland forest cover. An increase in tree cover indicates restoration efforts and may increase carbon dioxide absorption by trees, increase transpiration, and regulate climatic conditions (Table 6).

Table 5. Forest use/cover statistics for the Kafunjo forest ecosystem between 2023 and 2025.

Land Use/Cover	2023		2025		Change	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Tree cover	4.44	29.20	8.31	54.69	3.87	25.49
Grassland	10.18	67.00	6.38	41.99	−3.80	−25.01
Cropland	0.58	3.79	0.50	3.32	−0.07	−0.47

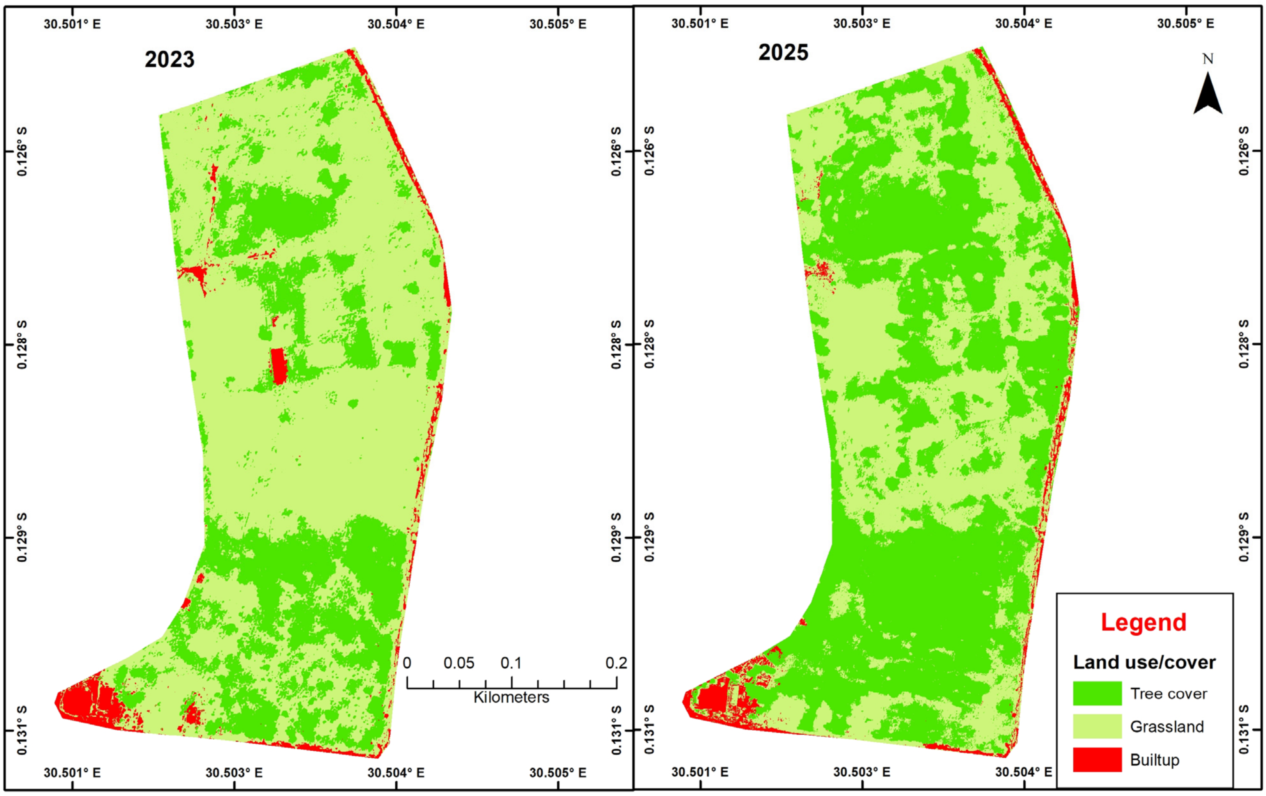

Figure 4. Forest use/cover analysis for Kafunjo forest ecosystem between 2023 and 2025.

Table 6. Transition analysis for Kafunjo forest ecosystem between 2023 and 2025.

		2023 (ha)			
	Land use/cover	Tree cover	Grassland	Cropland	Total
2025	Tree cover	3.74	4.47	0.09	8.31
	Grassland	0.67	5.57	0.13	6.38
	Cropland	0.02	0.13	0.35	0.50
	Total	4.44	10.18	0.58	15.19

The Mutufu forest ecosystem is located in the upper Sironko River catchment, in Mutufu ward, Mutufu town council, Sironko district. It is a restored site with EBA restoration initiatives. In the baseline land-cover assessment, grassland was the dominant land use/cover type, accounting for more than half of the total ecosystem area. Tree cover and cropland in the same baseline year of assessment occupied 23.63% and 14.99%, respectively, while open water occupied less than 5%. In 2025, tree cover dominated the landscape, covering more than 50%, nearly doubling the initial assessment value (Table 7 and Figure 5). An increase in tree cover occurred at the expense of mainly grassland and cropland by 3.79 ha and 1.22 ha, respectively. The reduction in anthropogenic land use/cover types, particularly cropland, indicates ecosystem regeneration. As tree cover increases and dominates the ecosystem, the rates of carbon dioxide sequestration, evapotranspiration, and heat regulation are optimized, thereby mitigating climate change (Table 8).

Table 7. Forest use/cover statistics for the Mutufu forest ecosystem between 2023 and 2025.

Forest Use/Cover	2023		2025		Change	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Tree cover	2.68	23.62	5.94	52.36	3.26	28.75
Grassland	6.75	59.46	4.46	39.29	−2.29	−20.17
Cropland	1.70	14.99	0.73	6.41	−0.97	−8.58
Open water	0.22	1.93	0.22	1.93	0.00	0.00

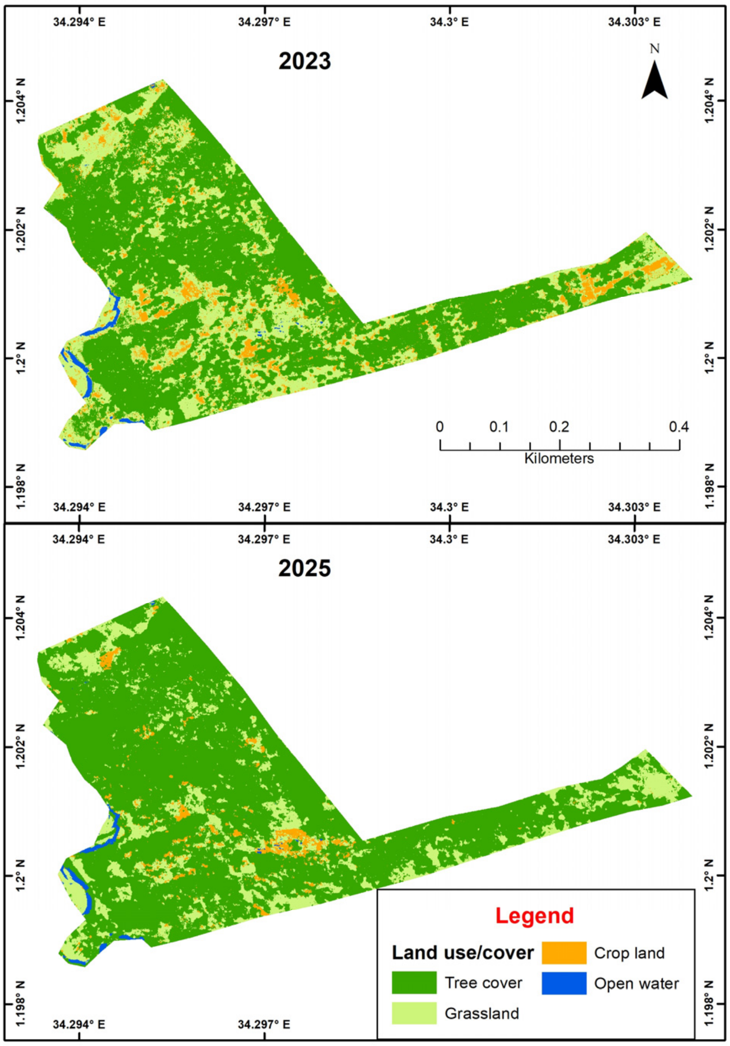

Figure 5. Forest use/cover analysis for the Mutufu forest ecosystem between 2023 and 2025.

Table 8. Transition analysis for the Mutufu forest ecosystem between 2023 and 2025.

	2023 (ha)					
	Land use/cover	Tree cover	Grassland	Cropland	Open water	Total
2025	Tree cover	1.22	3.79	0.94	-	5.94
	Grassland	1.21	2.56	0.69	-	4.46
	Cropland	0.25	0.40	0.08	-	0.73
	Open water	-	-	-	0.22	0.22
	Total	2.68	6.75	1.70	0.22	11.35

3.1.2. Drivers of Wetland and Forest Ecosystem Degradation

This study hypothesized that anthropogenic factors are not the significant causes of wetland and forest degradation. The results on the perceived causes of wetland and forest ecosystem degradation reported by households in the studied sites are presented in Table 9. The study results demonstrate that degradation of wetland and forest ecosystems is primarily attributable to human-induced disturbances. The most significant ($p \leq 0.05$) causes of ecosystem degradation included poverty, excessive water abstraction, population increase, burning of vegetation, soil erosion from nearby farms, overharvesting of wetland resources, overgrazing along wetlands, cultivation in wetlands, construction of roads and valley dams, and invasion of alien species. Evidence indicates that livelihood pressures and unsustainable resource-use practices are key drivers of ecosystem degradation, necessitating targeted interventions that address both poverty alleviation and sustainable land and water management.

Table 9. Drivers of wetland/forest degradation in the restored and unrestored areas.

Drivers of Degradation	**Restored Wetland (*n*, %)**	**Unrestored Wetland (*n*, %)**	**Wetland *p*-Value**	**Forest Restored (*n*, %)**	**Forest Unrestored (*n*, %)**	**Forest *p*-Value**
Poverty	12 (7)	45 (7)	0.001	66 (9)	40 (6)	0.001
Excessive Water Abstraction	33 (19)	10 (2)	0.03	65 (9)	15 (2)	0.03
Population Increase	17 (10)	12 (2)	0.034	68 (10)	18 (3)	0.034
Burning of Wetland/Forest Vegetation	9 (5)	4 (1)	0.012	66 (9)	5 (1)	0.012
Soil Erosion (Nearby Farms)	30 (17)	10 (2)	0.002	78 (8)	88 (9)	0.002
Tree Planting	1 (1)	4 (1)	0.045	61 (9)	8 (1)	0.045
Over-Harvesting of Wetland Resources	3 (2)	7 (1)	0.033	56 (8)	6 (1)	0.028
Political Interferences	1 (1)	2 (0)	0.056	60 (8)	4 (0)	0.056
Overgrazing (Wetlands and Riverbanks)	17 (10)	10 (2)	0.013	25 (4)	6 (1)	0.013
Brick Making	2 (1)	3 (1)	0.249	49 (5)	48 (5)	0.249
Infrastructural Developments (e.g., Industries)	5 (3)	6 (1)	0.233	43 (6)	8 (1)	0.233
Construction of Roads and Valley Dams	8 (5)	4 (1)	0.046	39 (4)	—	0.024
Unclear Land Tenure	1 (1)	3 (1)	0.087	28 (3)	26 (3)	0.087
Cultivation in Wetlands	21 (12)	9 (2)	0.014	0 (0)	5 (1)	0.014
Sand and Clay Mining	5 (3)	7 (1)	0.127	21 (2)	16 (2)	0.127
Channeling Water from Wetlands	1 (1)	3 (1)	0.003	13 (2)	4 (1)	0.003

Table 9. *Cont.*

Drivers of Degradation	Restored Wetland (*n*, %)	Unrestored Wetland (*n*, %)	Wetland *p*-Value	Forest Restored (*n*, %)	Forest Unrestored (*n*, %)	Forest *p*-Value
Limited Awareness / Poor Knowledge	7 (4)	5 (1)	0.289	4 (1)	8 (1)	0.672
Establishment of Washing Bays	0 (0)	1 (0)	0.413	15 (2)	5 (1)	0.055
Invasion of Alien Species	0 (0)	3 (0)	0.008	12 (1)	9 (1)	0.019
Dumping of Solid Waste and Industrial Effluents	4 (2)	2 (0)	0.257	5 (1)	6 (0)	0.328
Total	177 (100)	98 (100)		719 (100)	298 (100)	

3.2. The Effects of Wetland/Forest Restoration on Ecosystem Services

3.2.1. Implemented Ecosystem Restoration Measures

This study shows that, in wetland ecosystems, the most significant wetland-based adaptation interventions implemented were mobilization and sensitization of communities on wetland restoration, wetland demarcation, revegetation, establishment of flood control measures, and provision of alternative livelihoods (fruit growing) ($p \leq 0.05$). The non-crucial ecosystem-based adaptation measures promoted included sensitization on the risks of fishing and sand mining, demarcation of flood zones, beekeeping, fish farming, and the implementation of soil and water conservation measures (Table 10). These results demonstrate that physical/direct ecosystem-based adaptation measures are preferred for restoring wetlands.

Table 10. Ecosystem restoration measures implemented to restore forest and wetland ecosystems.

Wetland Restoration Measures	Coeff	Std. Err.	Z	*p*-Value
Mobilization and sensitization on restoration	−1.52	0.54	−2.81	0.005
Buffer zone demarcation	−1.38	0.54	−2.57	0.011
Wetland boundary demarcation	−1.02	0.48	−2.13	0.032
Revegetation	0.95	0.48	1.98	0.049
Sensitization on fishing/sand mining	0.8	0.47	1.72	0.088
Demarcation of flood zones	0.88	0.48	1.86	0.065
Flood control strategies	1.37	0.56	2.43	0.015
Beekeeping	−0.61	0.49	−1.23	0.217
Fruit growing	1.17	0.58	2.04	0.042
Fish farming	0.89	0.58	1.53	0.126
Soil and water conservation	0.97	0.59	1.65	0.098
Constant (Intercept)	−0.37	0.09	−4.11	0
Forest restoration measures	Coeff	Std. Err.	Z	*p*-Value
Mobilization and sensitization	−1.12	0.49	−2.32	0.021
Buffer zone demarcation	−1.13	0.46	−2.47	0.014
Forest boundary demarcation	−0.73	0.36	−2.06	0.04
Revegetation	1.36	0.61	2.24	0.025
Sensitization on fishing/sand mining	3.18	1.03	3.09	0.001
Demarcation of flood zones	1.61	0.67	2.39	0.017

Table 10. *Cont.*

Wetland Restoration Measures	Coeff	Std. Err.	Z	*p*-Value
Flood control strategies	2.29	0.88	2.6	0.01
Beekeeping	1.32	0.76	1.61	0.082
Fruit growing	1.4	0.64	2.18	0.029
Fish farming	1.95	1.04	1.88	0.063
Soil and water conservation	−0.1	0.41	−0.78	0.437
Constant (Intercept)	−0.28	0.08	−3.5	0.001

In forest ecosystems, the most significant ecosystem-based adaptation interventions implemented to restore them were mobilization and sensitization of communities to ecosystem-based adaptation measures, forest buffer zone and forest boundary demarcation, revegetation, sensitization to deforestation, and promotion of agroforestry (fruit cultivation) ($p \leq 0.05$). The wetland and forest ecosystems were largely restored through natural regeneration, owing to their adaptive capacity to local climatic and soil conditions, thereby helping to reclaim degraded land. These measures were applied across both permanent and seasonal wetland ecosystems in the study areas, whereas in forests, they were used only in natural forests.

3.2.2. Effects of Wetland/Forest Restoration Measures on Ecosystem Services Supply

From logistic regression results (Table 11), it was revealed that all ecosystem services (provisioning, regulatory, cultural, and supporting) were enhanced by wetland restoration (OR > 1). The most enhanced ecosystem services were provisioning, attributed to vegetation recovery increasing the availability of vegetation-related products, and water availability, followed by supporting services, including increased wildlife diversity and vegetation species. There is a statistically significant difference in vegetation recovery and increase, tree and plant restoration (phoenix, bamboo), wetlands and swamps recovery, vegetation species introduction and diversity, and wildlife and birds observed ($p < 0.05$). The results imply that wetland restoration is statistically proven to enhance the supply of ecosystem services, particularly provisioning and supporting services, making it an evidence-based and practical approach for both conservation and rural livelihood improvement.

Table 11. Effects of wetland and forest restoration on the recovery and supply of ecosystem services.

Ecosystem Services	Wetland Restoration OR (95% CI)	*p*-Value	Forest Restoration OR (95% CI)	*p*-Value
Water level increase	1.25 (0.45–3.42)	0.241	2.10 (0.62–7.18)	0.241
Vegetation Recovery increases	3.82 (1.95–7.45)	0.001	1.90 (0.50–6.72)	0.001
Tree and Plant Restoration (Phoenix, Bamboo)	2.70 (1.25–5.83)	0.001	1.00 (–)	0.001
Vegetation Species Introduction and Diversity	4.10 (1.75–9.64)	0.001	1.00 (–)	0.001
Wildlife and Birds Observed	1.85 (1.02–3.42)	0.025	1.00 (–)	0.025
Wetlands and Swamps Recovery	5.35 (2.48–11.5)	0.001	1.00 (–)	0.001
Pollination	1.65 (0.54–5.01)	0.108	1.00 (–)	0.108
Disaster Risk Reduction	1.52 (0.48–4.77)	0.108	1.00 (–)	0.108
No Change/No Observation	0.95 (0.38–2.38)	0.531	0.10 (0.01–0.89)	0.089

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For forest ecosystem restoration, the most enhanced ecosystem services were also provisioning services, including vegetation recovery and products, and water level increase (OR > 1). However, no enhancement in ecosystem services was observed, including tree and plant restoration (phoenix, bamboo), vegetation species introduction and diversity, wildlife and birds observed, and pollination (OR = 1). There was a statistically significant difference in the enhancement of ecosystem services, including vegetation recovery and increase, tree and plant restoration (phoenix, bamboo), vegetation species introduction and diversity, and wildlife and birds observed ($p < 0.05$). This difference indicates that forest restoration significantly enhances biodiversity and ecological recovery. Although some forest services showed weaker statistical associations compared to wetlands, households consistently recognized tangible ecosystem services (provisioning and supporting) more than intangible cultural or regulating services.

3.3. Perceived Comparison in the Supply of Ecosystem Services Between the Restored and Unrestored Communities

The binary logistic regression results indicate that restoration significantly influences the supply of several ecosystem services in both wetland and forest ecosystems (Table 12). In wetlands, provisioning ecosystem services indicators, including an increase in pastures for grazing animals, enhanced production of livestock yield, increased soil productivity and crop yields, and new income opportunities, health-related benefits from crops and livestock products, and supporting services were reported more (OR > 1) in restored communities compared to the unrestored. Contrary to this, regulating services indicators, including water purification and reducing vulnerability to disasters, and cultural ecosystem services indicators, including increases in recreation and tourism and enhanced scenic beauty, were reported more (OR < 1) in unrestored communities compared to restored communities. Services, including increased income, improved livestock production, increased soil productivity and crop yields, better health from crop/livestock products, water purification, and enhanced scenic beauty, reported statistically significant differences in supply ($p < 0.05$) between the restored and unrestored communities. These results imply that wetland restoration enhances both material and livelihood-related ecosystem services.

Table 12. Perceived comparisons of ecosystem services supply between restored and unrestored wetland and forest ecosystems.

Ecosystem Service Categories	Ecosystem Service Indicators	Wetland Ecosystem OR (95% CI)	*p*-Value	Forest Ecosystem OR (95% CI)	*p*-Value
Provisioning Services	Increases in pastures for grazing animals	1.12 (0.75–1.67)	0.58	(0.72–1.07)	0.19
	Increase in income	0.63 (0.40–0.97)	0.035	(0.50–0.85)	0.002
	Enhanced production of livestock yield	7.33 (2.10–25.5)	0.002	(0.63–1.08)	0.15
	Increased soil productivity and crop yields	5.67 (1.57–20.5)	0.008	(0.55–1.07)	0.11
	Better health from crop/livestock products	3.33 (1.05–10.5)	0.042	(0.54–1.07)	0.11
	Reduction in crop pests and diseases	9.00 (0.50–162)	0.13	1 (0.77–1.73)	0.5

Table 12. *Cont.*

Ecosystem Service Categories	Ecosystem Service Indicators	Wetland Ecosystem OR (95% CI)	*p*-Value	Forest Ecosystem OR (95% CI)	*p*-Value
	Reduction in livestock pests and diseases	7.00 (0.80–61.0)	0.08	1 (0.78–2.22)	0.3
	New income opportunities	15.0 (5.3–42.5)		0.001 (0.87–1.50)	0.33
Regulating Services	Water purification	0.54 (0.36–0.81)	0.003	(0.41–0.68)	0.001
	More diverse habitats (predators and prey)	1.23 (0.71–2.14)	0.45	0 (0.53–0.90)	0.007
	Reducing vulnerability to disasters	0.38 (0.14–1.05)	0.06	0 (0.32–0.67)	0.001
Cultural Services	Increases in recreation and tourism	0.53 (0.25–1.11)	0.09	(0.53–0.97)	0.03
	Enhanced scenic beauty	0.45 (0.21–0.95)	0.036	(0.45–0.91)	0.014
Supporting Services	Habitat provision and biodiversity support	1.31 (0.56–3.06)	0.53	0 (0.47–1.02)	0.05

In forest ecosystems, provisioning ecosystem services indicators, including increases in pastures for grazing animals, enhanced production of livestock yield, increased soil productivity and crop yields, an increase in income, health-related benefits from crops and livestock products, and all regulating and supporting services were reported more (OR > 1) in unrestored communities compared to restored communities. Ecosystem services indicators, including increased income, increased recreation and tourism, and enhanced scenic beauty, showed statistically significant differences in supply ($p < 0.05$) between the restored and unrestored communities. The results imply that unrestored communities are perceived as providing greater livelihood and ecological benefits, indicating the need to align restoration efforts with strategies that deliver both immediate and long-term community benefits.

3.4. Comparison in the Recovery of Ecosystem Services Between the Wetland and Forest Ecosystems

The logistic regression results in Table 13 indicate that provisioning ecosystem services indicators, including increase in pastures for grazing animals, enhanced production of livestock yield, increased soil productivity and crop yields, and new income opportunities, health-related benefits from crops and livestock products, and regulating services indicators, including water purification, more diverse habitats (predators and prey), and supporting services, recovered more (OR > 1) in the wetland ecosystem than in the forest ecosystem. On the contrary, regulating ecosystem service indicators, including reducing vulnerability to disasters, and cultural service indicators, including increases in recreation and tourism and enhanced scenic beauty, recovered more (OR < 1) in the forest ecosystem than in the wetland ecosystem. However, these differences are not statistically significant ($p > 0.05$). These results indicate that both ecosystem types contribute meaningfully to community livelihoods and environmental resilience. Still, restoration strategies need to be enhanced to align with the specific service categories unique to each ecosystem.

Table 13. Comparison of the supply of ecosystem services between the restored and unrestored communities.

Ecosystem Service Categories	Ecosystem Service Indicators	OR (Wetland vs. Forest) (95% CI)	*p*-Value
Provisioning Services	Increases in pastures for grazing animals	1.28 (0.95–1.73)	0.1
	Increase in income	0.97 (0.70–1.35)	0.85
	Enhanced production of livestock yield	1.15 (0.85–1.55)	0.36
	Increased soil productivity and crop yields	1.12 (0.78–1.60)	0.53
	Better health from crop/livestock products	1.05 (0.73–1.52)	0.78
	Reduction in crop pests and diseases	1.30 (0.80–2.10)	0.29
	Reduction in livestock pests and diseases	1.25 (0.72–2.15)	0.44
	New income opportunities	1.10 (0.80–1.50)	0.55
Regulating Services	Water purification (quality and quantity)	1.08 (0.80–1.46)	0.62
	More diverse habitats (predators and prey)	1.15 (0.83–1.60)	0.39
	Reducing vulnerability to disasters	0.82 (0.55–1.21)	0.32
Cultural Services	Increases in recreation and tourism	0.78 (0.55–1.12)	0.18
	Enhanced scenic beauty	0.89 (0.60–1.31)	0.56
Supporting Services	Habitat provision and biodiversity support	1.05 (0.68–1.61)	0.83

4. Discussion

4.1. Spatial Extent and Drivers of Wetland and Forest Ecosystem Degradation

The observed increase in papyrus and grassland cover and a significant decrease in cropland and built-up areas in the Rwambu restored wetland indicate a gradual restoration of the ecosystem, transitioning towards a more functional wetland ecosystem. Papyrus restoration is an eco-hydrological tool that can improve water quality and moderate the local climate by regulating the water cycle. An increase in papyrus, for instance, suggests that the restoration efforts had a positive and significant impact on wetland management. Restoration activities in degraded wetland systems can facilitate the full recovery of the wetland ecosystem compared to the absence of interventions. The observed reduction in tree cover within the Rwambu wetland indicates a decline in tree plantations resulting from restoration.

Both Kafunjo and Mutufu forests exhibited significant increases in tree cover between 2023 and 2025, indicating successful restoration efforts. The reduction in anthropogenic land use/cover types, especially cropland, highlights a regenerating ecosystem. As tree cover dominates the ecosystem, the rates of carbon dioxide sequestration, evapotranspiration, and heat regulation are streamlined, thereby mitigating the effects of climate change. Natural regeneration and enrichment planting can accelerate forest recovery, enhancing carbon sequestration and biodiversity. However, caution is warranted, as rapid afforestation can alter hydrological processes by reducing streamflow and groundwater recharge through

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increased evapotranspiration. Therefore, these results underscore the effectiveness of EbA restoration in reversing degradation trajectories, enhancing vegetation cover, and supporting ecosystem functions. The persistence of degradation in unrestored ecosystem sites indicates the risks of inaction, emphasizing the need for continuous restoration efforts to maintain and enhance ecosystem services.

The study establishes that wetland and forest ecosystems are significantly degraded by direct, human-induced activities, especially agricultural activities. The predominance of farming activities underscores the link between local livelihoods and ecosystem degradation. These findings are consistent with studies conducted in East Africa [35,36] that show that agricultural expansion, resource overexploitation, and unsustainable land use are the primary drivers of wetland and forest degradation. Practices such as wetland cultivation and the establishment of Eucalyptus plantations in buffer zones exacerbate environmental stress by disrupting soil and overusing water [37]. As asserted by Ref. [38], communities living adjacent to wetlands and forests often depend heavily on these resources for food, water, fuelwood, and building materials, leading to their unsustainable exploitation. These findings indicate that wetland and forest management policies and strategies must address the increasing pressure from agricultural activities by promoting sustainable land use practices, enforcing buffer-zone regulations, and providing alternative livelihood options. The results affirm the argument that, in developing-country contexts, human forces tend to prevail over indirect or natural forces in the degradation of ecosystems [39]. Such an understanding can inform integrated conservation policies that simultaneously address poverty reduction and ecosystem restoration.

4.2. The Effects of Wetland and Forest Restoration on Ecosystem Services Supplies

The study revealed that community mobilization and sensitization, ecosystem boundary demarcation, revegetation, and the promotion of alternative livelihoods, such as fruit growing, are the most significant ecosystem-based adaptation (EbA) interventions for wetland and forest restoration. This is consistent with previous studies emphasizing participatory approaches. Studies, e.g., [40], underline that community engagement promotes adaptive capacity and ensures sustainability in ecosystem restoration. Similarly, Ref. [36] reports that boundary demarcation and active revegetation are critical interventions for restoring degraded wetlands, facilitating recovery of hydrological functions and biodiversity.

In forest ecosystems, agroforestry has been widely recognized for its benefits of ecological restoration and livelihood improvement. Refs. [41–43] explain that agroforestry systems enhance biodiversity, improve soil quality, and provide economic resilience for local communities, especially in tropical landscapes. Such restoration initiatives lead to significant biodiversity recovery and carbon sequestration without intensive planting efforts [44]. These findings collectively underscore the importance of integrated restoration strategies that combine physical restoration techniques, community participation, and natural ecosystem processes.

The study results showed that wetland restoration enhanced the supply of ecosystem services, particularly provisioning and supporting services, making it an evidence-based and practical approach for conservation and rural livelihood improvement. This is supported by findings from [45,46], which demonstrated that restored wetlands in Uganda enhanced provisioning services (e.g., vegetation recovery and water availability) and supporting services (e.g., increased biodiversity), highlighting the effectiveness of such interventions.

The observed significant enhancements in provisioning services, including vegetation recovery and water availability, and in supporting services in restored forests, were accompanied by a notable increase in biodiversity. These results are consistent with a study [11] on the Mpanga Central Forest Reserve in Kamengo Sub-County, Uganda, which found that forest products, including medicinal plants and fuelwood, support the livelihoods of communities adjacent to the forest. It is essential to focus on restoration initiatives that enhance provisioning and supporting services that directly affect livelihoods in communities.

4.3. Comparison of the Supply and Recovery of Ecosystem Services Between the Wetland and Forest Ecosystems

The current study indicated that restoration strongly influences the supply of ecosystem services, with restored wetlands showing clear gains in provisioning and supporting services. This aligns with observable evidence at the global and regional levels. A study by Ref. [47] found that vegetation recovery and re-wetting in wetlands quickly improve forage production, soil fertility, and wildlife diversity, benefits that are both ecologically significant and immediately visible to surrounding communities. Additionally, Ref. [48] reported that restored wetlands provided improved dry-season grazing and income opportunities, confirming that livelihood-related services are the most readily perceived outcomes of restoration by many communities. These findings underscore that wetland restoration not only delivers ecological benefits but also generates direct socioeconomic gains, thereby strengthening community support for restoration initiatives.

By contrast, the forest ecosystem results indicate that households in unrestored communities perceive greater provisioning and cultural services, including income, grazing, and scenic beauty, than those in restored forest communities. This perception is consistently observed in other studies, which show that forest restoration often restricts short-term access to resources, delaying immediate livelihood benefits. Many communities value degraded forests more in the short run because of their accessibility for fuelwood, timber, and grazing land, even though restoration provides long-term benefits for regulating and supporting services [49]. These outcomes indicate that forest restoration requires careful alignment with livelihood strategies, participatory planning, and communication about long-term benefits to sustain community support.

Although this study was conducted at the local level, the results are of global importance in informing restoration interventions and climate adaptation, especially in tropical areas. This study assessed the effects of forest and wetland restoration 2 years post-restoration; however, within this period, the forests may not have fully recovered. This implies that comparisons between wetland and forest ecosystem service recoveries may be inconclusive. Further studies should analyze the impacts of restoration after a period of at least 4 to 5 years, and interlink wetland and forest spatial degradation and restoration. Secondly, ecosystem recovery assessments should include physical monitoring of biodiversity and water quality rather than relying on community perceptions.

5. Conclusions

The study results demonstrate that wetland and forest ecosystem degradation is attributed to human-induced disturbances (poverty, excessive water abstraction, population increase, burning of vegetation, soil erosion from nearby farms, overharvesting of wetland resources, and overgrazing along wetlands and riverbanks). Evidence indicates that livelihood pressures and unsustainable resource-use practices are key drivers of ecosystem degradation, necessitating targeted interventions that address both poverty alleviation and sustainable land and water management.

The most significant wetland ecosystem-based adaptation interventions implemented to restore wetlands were community mobilization and sensitization on wetland restoration, wetland demarcation, revegetation, the establishment of flood control measures, and the provision of alternative livelihoods. The wetland and forest ecosystems were largely restored through natural regeneration, owing to their adaptive capacity to local climatic and soil conditions, thereby helping to reclaim degraded land. These measures were applied across both permanent and seasonal wetland ecosystems in the study areas, whereas in forests, they were used only in natural forests. The study shows that wetland restoration enhances both material and livelihood-related ecosystem services. These results indicate that both ecosystem types contribute meaningfully to community livelihoods and environmental resilience. Still, restoration strategies need to be enhanced to align with the specific service categories unique to each ecosystem.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su18031685/s1. Image classification accuracy assessment for Rwambu and Mutufu wetlands, and Kafunjo and Mutufu forest ecosystems.

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Institutional Review Board Statement: This study is exempt from ethical review by the Institutional Committee because it adheres to the Ministry of Water and Environment's ecosystem restoration guidelines.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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