



The economic value of ecosystem services from restored grasslands in Kenya

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ABSTRACT

Grasslands in arid and semi-arid regions provide critical ecosystem services that support pastoral livelihoods, biodiversity conservation, and climate adaptation. However, the economic implications of grassland degradation and restoration under increasing drought pressure remain poorly understood. This study evaluates how potential alternative grassland ecological trajectories (degraded annual-dominated systems versus restored perennial-dominated systems) could affect the economic flow of ecosystem services under drought conditions in northern Kenya. Ecosystem service values were estimated using a value transfer approach based on the Ecosystem Services Valuation Database and applied to the Ewaso Ng'iro North catchment. Two vegetation scenarios were modeled to represent contrasting land management pathways and their responses to severe drought. Results indicate that annual-dominated grasslands could potentially experience a substantially greater decline in ecosystem service value during drought compared to perennial-dominated systems, reflecting the greater ecological resilience of restored grasslands. At the landscape scale, this difference represents a large potential loss in ecosystem service flows associated with degraded systems. A simplified incremental benefit-cost analysis, based on the difference in ecosystem service value between perennial and annual grasslands, resulted in estimated benefit-cost ratios of 0.32 for earth bund construction and 32.4 for Holistic Land and Livestock Management, with the difference primarily reflecting the substantially lower per-hectare implementation cost of the latter. While the monetary estimates presented here should be interpreted as indicative rather than precise valuations, the results illustrate how ecosystem service assessment and incremental benefit-cost analysis can inform restoration investment decisions in dryland landscapes facing increasing climate variability.

1. Introduction

At the heart of the current environmental global crisis is the undervaluation of natural capital, where markets, policies and institutions are not considering the crucial dependency of society's well-being on ecosystem services (Hernández-Blanco & Costanza, 2019). Because many ecosystem services (especially regulating and cultural services) are public goods, markets for them do not exist and therefore there is limited potential to manage them with conventional economic and financial approaches. And because of the difficulties in estimating the value of non-marketed services, ecosystems are often undervalued in cost-benefit analysis of conservation versus commercial land and sea uses, causing their degradation and loss globally (Daly & Farley, 2004; Costanza, 2022). To overcome these market failures, the economic valuation of ecosystem services has been conducted at multiple

geographical scales all over the planet for more than two decades (Costanza et al., 2017; Costanza et al., 2014). The main goal of estimating the value of ecosystem services is to demonstrate how protecting, restoring and sustainably using natural resources not only has positive outcomes in securing the health of ecosystems, but also represents an investment that yields multiple benefits to the wellbeing of local communities (Murdoch et al., 2007; Murdoch et al., 2010; Balmford et al., 2002).

In the case of drylands, these ecosystems cover around 41 % of the planet, supporting close to 38 % of the world's population through ecosystem services such as clean air and water, forage for livestock and wildlife, opportunities for tourism and recreation, and raw materials, among many others. Nevertheless, 10–20 % of arid and semiarid rangelands are currently degraded, and this percentage increase to 70 % when only considering sub-Saharan Africa (UNCCD, 1994),

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characterized by a loss of perennial plant cover and the consequent increase in bare ground (Kimiti, Riginos, et al., 2017). This degradation has a significant impact on the provision of benefits to people and therefore it is a direct threat to the local communities' well-being. In Kenya, grasslands are not only ecological assets, but they are also vital socio-economic systems. They support millions of pastoralists and agro-pastoralists who rely on extensive rangeland systems for livestock production (Nyariki & Amwata, 2019). Moreover, these ecosystems sustain iconic wildlife species that underpin the country's tourism economy, one of the largest foreign exchange earners (Holland et al., 2022).

The cost of losing grassland ecosystems is profound and escalating. Degraded grasslands are less productive, less biodiverse, and less able to buffer against environmental shocks. As Kenya faces an increasing incidence of multi-year droughts, the lack of investment in grassland resilience could produce significant social and economic costs (Herrick et al., 2016). Furthermore, without meaningful recognition of their economic value, grasslands remain at risk of conversion to unsustainable land uses. In Samburu, Isiolo and Laikipia counties, land degradation has increased bare ground and provided suitable conditions for the spread of plant species such as *Acacia reficiens* (an indigenous encroacher) and *Opuntia stricta* (an invasive alien plant), replacing perennial grasses and reducing forage availability (Kimiti, Hodge, et al., 2017). In addition, the introduction and rapid spread of the invasive alien plant *Prosopis juliflora* is a major threat to grass cover in northern Kenya, with studies from Ethiopia showing that it reduces grass species from seven to two in areas it has invaded (Kebede & Coppock, 2015).

Therefore, restoration of grasslands is increasingly being recognized as a strategic investment in climate adaptation and resilience. Through the improvement of vegetation cover, restoring native grasses, and controlling invasive alien species and indigenous encroachers, restoration interventions can help stabilize soils, increase groundwater recharge, and moderate local temperatures. These changes directly benefit both people and wildlife, where communities gain more reliable sources of pasture and water, while wildlife, particularly migratory herbivores, benefit from more extensive and nutritionally diverse habitats. Furthermore, the co-benefits of restoration extend beyond ecological resilience to include reduced conflict over resources, improved health outcomes, and greater livelihood security (Reid et al., 2014).

To address this challenge, the Grevy's Zebra Trust (GZT), an independent wildlife conservation Trust in Kenya dedicated towards protecting the endangered Grevy's zebra, started restoration efforts on grasslands in 2009 in the Westgate Community Conservancy with a clearing pilot project, where approximately 238 ha of land was cleared of *Acacia reficiens* and reseeded with *Cenchrus ciliaris* (perennial grass highly used in other restoration efforts throughout the country). This was coupled with holistic planned grazing, where the land around the restoration area was divided into grazing blocks and cattle were grazed in one concentrated herd based on a grazing calendar. Subsequent studies of these plots demonstrated that these restoration strategies resulted in an increase of more than 25 % ground cover, 34 % perennial grass cover, and 60 % standing herbaceous biomass, with the restored vegetation primarily composed of native grass species typical of the local rangeland ecosystem (Kimiti et al., 2020).

More recently, the GZT has implemented restoration at the small scale through the use of soil erosion structures called semi-circular bunds or half-moons, which work by trapping sediment and slowing down surface run-off (Ludwig & Tongway, 1996). Comparable barriers in other areas of the region have demonstrated a capacity to establish substantial vegetation patches, particularly when reseeding with perennial grasses is also implemented (Kimiti et al., 2017). The GZT's Rangelands Program is designed to use grazing planning and the associated cattle corrals (bomas) to encourage the regeneration of perennial grasses across the landscape by preventing overgrazing. These bomas act as nutrient concentration hotspots due to dung deposits that eventually create persistent perennial vegetation patches if managed correctly

(Porensky & Veblen 2015). The GZT's current strategy for improving rangeland health is encapsulated by its Regenerating Rangelands goal. This long-term program focuses on planned grazing to restore degraded rangeland, benefiting both wildlife and pastoralist communities. At its core is Holistic Land and Livestock Management (HLLM), which encourages year-round grazing planning, rotating grazing areas and using livestock trampling to break the compacted soil surface, aerate it, and improve nutrient cycling thereby boosting water infiltration and plant regeneration.

While ecosystem service valuation studies have been widely applied across different ecosystems, fewer studies have explicitly examined how restoration-driven changes in vegetation composition influence the resilience of ecosystem service flows under drought conditions. In dryland rangelands, shifts between annual-dominated and perennial-dominated grassland systems can significantly alter ecosystem functioning, affecting forage stability, soil carbon dynamics, and water regulation. This study therefore uses ecosystem service valuation as a decision-support tool to explore how alternative grassland ecological trajectories may influence the economic flow of ecosystem services under drought scenarios, comparing two contrasting vegetation trajectories: (1) degraded grasslands dominated by annual species and (2) restored systems with a higher proportion of perennial grasses. The objective is not to produce precise monetary estimates, but rather to compare how different land management pathways may affect ecosystem service resilience and the economic rationale for restoration investments.

2. Methods

2.1. Study area

This study focuses in the Ewaso Ng'iro North Catchment Area in Kenya, with an altitude range from 150 masl in Lorian to 5199 masl in Mount Kenya. This area has an average annual daily temperature of 15–37°C, and annual minimum night temperatures of 3–23°C. The average annual precipitation is 380 mm, although this varies geographically, where the southwestern parts receive over 1000 mm and the central and eastern parts receive less than 300 mm. Furthermore, rain patterns vary annually, with long rains during the months of March – May, and short rains during October – November. 70 % of the basin is classified as arid and semi-arid lands (ASAL). These areas are used as grazing grounds for domestic (e.g., cattle, camels, sheep and goats) and wild herbivores (e.g., Grevy zebra).

Samburu County is part of the Ewaso Ng'iro North Catchment Area, where the majority of the ecosystem is mixed-use semi-arid rangeland supporting both cattle and wildlife. The ground cover in Samburu County is dominated by a mixture of annual and perennial grasses and forbs (e.g., *Indigofera* spp., *Cynodon* spp., *Eragrostis* spp., and *Aristida* spp.). This ecosystem supports wildlife species such as elephants (*Loxodonta africana*), impalas (*Aepyceros melampus*) and Grevy's zebras (*Equus grevyi*) (Kimiti et al., 2020). Here, there has been a perceived reduction in the cover and diversity of perennial grasses, and at the same time an increase in woody vegetation (e.g., *Acacia reficiens* substituting grassland) and bare ground prevalence (Kimiti, Hodge, et al., 2017). Laikipia County has a higher annual precipitation in comparison with Samburu, causing a higher vegetation productivity, but as in the case of Samburu, there are historical reports that point to a significant increase of shrub cover that has substituted grasslands (Kimiti et al., 2017) (Fig. 1).

The GZT is currently conducting restoration efforts in this area, working with communities in Samburu and Isiolo, including on clearing indigenous encroachers (*A. reficiens*), constructing semicircular bunds, and implementing HLLM. One of the key objectives of these restoration strategies, especially that of clearing, is to change the composition of the grasslands, moving from annual grasses to perennials. This should in turn increase the resilience of the ecosystem to droughts and therefore

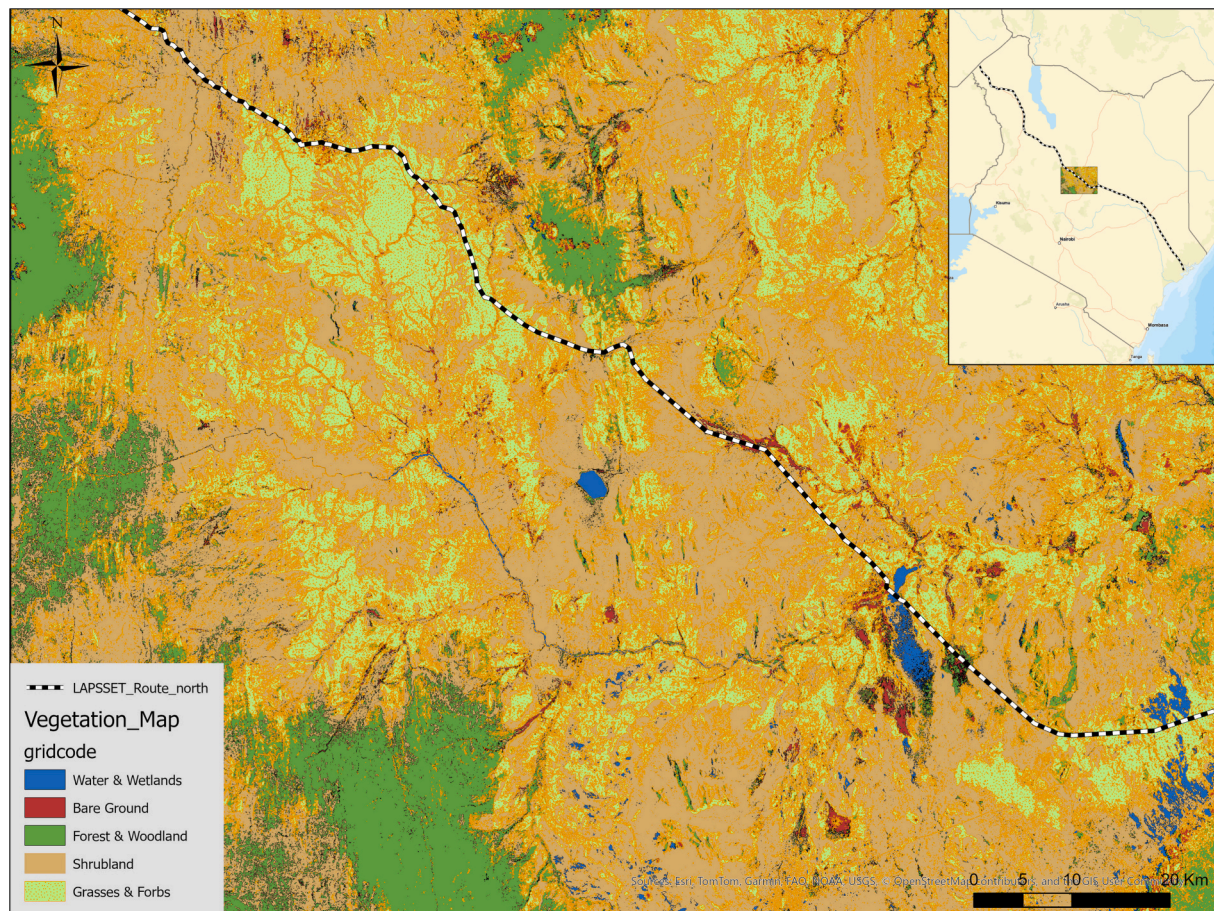


Fig. 1. Study area in the Ewaso Ng'iro North catchment showing the grassland areas within the GZT primary zone of interest, which represent the area included in the ecosystem service valuation.

avoid the increase of bare ground prevalence and the consequent loss of ecosystem services.

Finally, under Kenya's Vision 2030, the country has several large-scale linear infrastructure projects under The Lamu Port–South Sudan–Ethiopia Transport Corridor (LAPSSET Corridor), which could have potential significant environmental impacts in this area. The LAPSSET Corridor aims to improve transport and logistics, promote regional integration, and boost trade and economic development in the region. Plans for the corridor include a crude oil pipeline from Lokichar to Lamu, new highways, and a standard gauge railway. The crude oil pipeline proponents are required to deliver a biodiversity net gain under IFC Performance Standard 6.

2.2. Value transfer

Due to time and budget constraints, it is often not possible to conduct original/primary studies to economically value ecosystem services (Wilson & Hoehn, 2006; Plummer, 2009), which has led to an increased use of secondary data for this purpose through valuation techniques such as value transfer. Value transfer consists of “applying estimates of economic values from one location to a similar place in another location” (Plummer, 2009). This study used a unit value transfer, which applies a median value taken from several study sites.

Economic values from studies were extracted from the Ecosystem Service Valuation Database (ESVD) (Brander et al., 2024), a freely available tool with over 6700 estimates from more than 950 studies distributed across all biomes, ecosystem services, and geographic regions. The ESVD is the largest existing repository of ecosystem service values and is therefore a key source of information. Specifically, the

value transfer consisted of 6 steps (Fig. 2).

Step 1. Select ecosystems to be evaluated.

Although the study area covers several ecosystem types (e.g., bare ground, forests, wetlands, grasslands and shrublands), this study is focused on grasslands as a first exercise to estimate the economic value of ecosystem services in this area. Grass species identified in the Samburu–Isiolo Game Reserve area can be classified into (1) annual, which dominate in degraded or recently disturbed areas and contribute to lower and more variable ecosystem service values (e.g., *Aristida adscensionis*, *Aristida papposa*, *Dactyloctenium aegyptium*), and (2) perennial, typically associated with more stable ecosystems offering sustained forage, erosion control, and carbon sequestration (e.g., *Cynodon dactylon*, *Sporobolus spicatus*, *Cenchrus ciliaris*) (Barkham & Rainy, 1976). This classification helped inform the proportional composition of annual vs. perennial grasses assigned to each land cover scenario, thereby guiding the selection of corresponding ESVD values for economic valuation.

To estimate the total area of grasslands, the GZT provided a map in shapefile format of the entire study area. The area of grasslands was extracted in QGIS using the information available in the attribute table. It is key to highlight that this spatial information does not make any distinction between annual and perennial grasses.

Step 2. Select ecosystem services.

The analysis focuses on ecosystem services that are most sensitive to grassland degradation and relevant to local livelihoods and ecological function. The following services were selected for this study:

1. Climate regulation: Grasslands across East Africa, including the semiarid regions of Samburu and Isiolo in Kenya, possess substantial soil carbon sequestration potential. Meta-analyses indicate that these

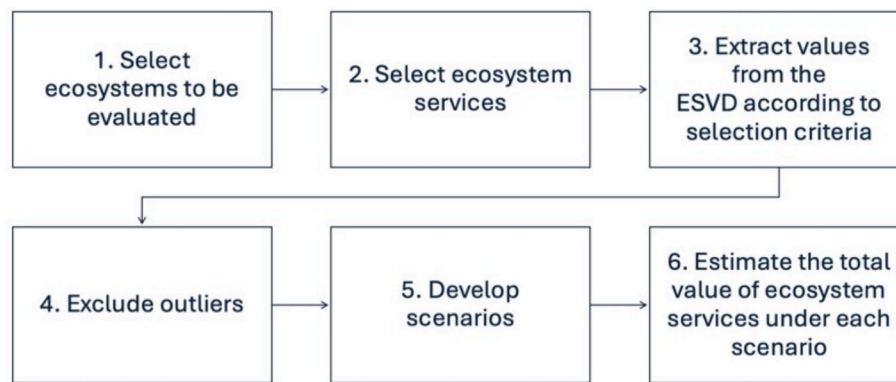


Fig. 2. Value transfer steps.

- grasslands can store between 3 and 93 tons of C per hectare in the upper 30 cm of soil, with sequestration rates ranging from 0.1 to 3. tons of C per hectare per year under improved grazing and restoration regimes (Tessema et al., 2020). Soil carbon stocks in grasslands are primarily determined by temperature and rainfall, with stocks being typically higher in cool humid climates (Tessema et al., 2020).
2. Existence, bequest values: Northern Kenya's grasslands host emblematic wildlife—such as Grevy's zebra, reticulated giraffe, and endemic birds—that hold strong non-use values, including existence and bequest values (Burgess et al., 2006). These values reflect the intrinsic importance society places on these ecosystems, and the desire to conserve them for future generations, even without direct interaction.
 3. Food: Grasslands underpin pastoralist food systems in northern Kenya by providing forage for cattle, goats, sheep, and camels, delivering milk, meat, hides, and income. Covering more than 60 % of land outside protected areas and hosting around 50 % of livestock, these ecosystems are central to regional food security (Mwangi, 2019).
 4. Medicinal resources: Grasslands are vital repositories of medicinal plant species used by local communities to treat a wide range of ailments, from respiratory infections to wounds and fevers. Ethnopharmacological research in northern Kenya documents over 130 species with validated antimicrobial or anti-inflammatory effects, underscoring the importance of biodiversity conservation for public health support in rural areas (Nanyingi et al., 2008).
 5. Opportunities for recreation and tourism: Grasslands in Kenya's semi-arid landscapes—particularly those within and adjacent to national reserves and wildlife conservancies—serve as critical habitats for megafauna such as elephants, lions, Grevy's zebras, and numerous endemic bird species. These ecosystems underpin nature-based tourism activities including wildlife safaris, birdwatching, and culturally immersive experiences with pastoralist communities. Community-run conservancies have become integral to this model, contributing significantly to tourism revenue and rural development (Bedelian, 2014).
 6. Raw materials: Grasslands yield essential household materials, perennial grasses for thatching, firewood, baskets, and mats (Lugusa et al., 2016). Climate change-driven livelihood strategies have increased reliance on these resources, especially among women artisans. Recent livelihood assessments indicate that sustainable harvesting of grassland biomass contributes substantially to household income and resilience (Opiyo et al., 2014).
 7. Regulation of water flows. Vegetation cover in grasslands regulates hydrology by promoting infiltration, moderating runoff, and supporting groundwater recharge. These services maintain seasonal flow stability in catchments of Samburu and Isiolo, contributing to water security for both ecosystems and communities. Degraded

grasslands, in contrast, exacerbate flood peaks and water scarcity (Mutuku et al., 2019).

8. Waste treatment: Grasslands play an indirect but critical role in the treatment of organic waste, particularly livestock manure, through natural decomposition and nutrient cycling. Soil microbial communities in these ecosystems facilitate the breakdown of organic matter and the removal of pathogens and excess nutrients, which improves soil fertility and water quality. In the absence of formal waste treatment infrastructure, especially in pastoral settlements, these ecological processes act as essential services supporting environmental health. Recent studies emphasize the role of grazing intensity and land management in maintaining soil biogeochemical functions in grasslands (Zhu et al., 2020).
9. Water: Grasslands serve as natural filters, mitigating sedimentation and nutrient loading in streams and wetlands. Their interception of runoff sustains perennial water sources in seasonal catchments (Hesla et al., 1985).

This selection allows a combination of all types of ecosystem services (i.e., provisioning, regulating, and cultural). The categories used here are based on the TEEB classification (TEEB, 2010), also used recently in Brander, De Groot, et al. (2024).

Step 3. Extract values from the ESVD according to selection criteria.

To select the economic values of the ecosystem services, the following study selection criteria were applied to reduce errors that can occur when using value transfer:

- Only studies that fall under the ecosystem category of “Tropical and Subtropical Savannas”, within the broader biome category of rangelands and grasslands. This subcategory was selected based on the ecological and socio-economic characteristics of the target area. Other ESVD subcategories such as temperate grasslands, hummock savannas, and temperate grassy woodlands were excluded due to fundamental differences in climatic regimes, vegetation types, and ecosystem service dynamics, which would undermine the reliability of transferred values.
- Only studies conducted in Africa, focusing on Kenya.
- Only studies that estimated values for each ecosystem service separately.
- Only studies that have determined the value of ecosystem services in spatial terms (i.e., values per hectare).
- Only primary studies, where the biophysical and economic estimates were made by the authors of each study, and therefore all studies that applied value transfer were excluded.
- The year of publication of the study from which the values were extracted was not considered in order to maintain a more extensive pool of values.

Step 4. Exclude outliers.

To ensure the robustness of the ecosystem services valuation analysis, outliers were identified and excluded using a two-stage process. First, all monetary values (\$Int 2020 ha⁻¹yr⁻¹) were transformed to their natural logarithms to reduce right skewness and stabilize the variance in the dataset. The interquartile range (IQR) method was then applied to the transformed values: outliers were considered those below the lower bound ($Q1 - 1.5 * IQR$) or above the upper bound ($Q3 + 1.5 * IQR$). These values were excluded from statistical calculations, such as median estimation, thus allowing for consistent and transparent identification of extreme values without distorting the central distribution of the data.

In cases where only two observations were available for a given ecosystem service, the IQR method was not applicable. Instead, a simple ratio check was used to assess comparability: if the highest value exceeded the lowest by more than 10 times, the service was flagged for manual review. In these situations, the most conservative (lowest) value was retained, or both values were excluded from the comparative analysis of medians between services, depending on the degree of disparity and the quality of the source.

Step 5. Develop scenarios.

The economic valuation of ecosystem services considered the following two hypothetical but ecologically plausible scenarios of grassland composition and behavior under drought conditions, with pre- and during-drought distributions defined, to have the area of the ecosystem under each scenario:

- **Scenario 1 – Annual grassland dominance (no restoration):** Prior to the drought, 80 % of the grassland area is composed of annual species and 20 % of perennial species. During a severe drought, annual grasses are highly susceptible to dieback, resulting in a 70 % reduction in their area, while perennial grasses experience a 20 % loss. Annual grasses are generally more vulnerable to drought stress than perennial species due to their shallower root systems and shorter life cycles (Knapp et al., 2008). This results in a during-drought landscape in which only 40 % of the original grassland cover remains: 24 % annuals and 16 % perennials. Among the surviving grasslands, the composition shifts to 60 % annuals and 40 % perennials.
- **Scenario 2 – Perennial grassland dominance (restoration):** In this scenario, restoration efforts are implemented to shift the grassland composition toward more drought-resilient perennial species. Before the drought, the landscape consists of 70 % perennials and 30 % annuals. During-drought, perennial grasses suffer only a 10 % loss, while annual grasses again face a 70 % reduction. This results in a total remaining grassland area of 72 %: 63 % perennials and 9 % annuals. The new composition of the surviving grassland cover is 87.5 % perennials and 12.5 % annuals.

It is important to highlight that while perennial grasses are generally more drought-tolerant than annuals, their actual resilience depends heavily on ecosystem condition and management history. In Scenario 1, perennials exist in a degraded landscape affected by poor soil conditions, compaction, and overgrazing, reducing their resistance to drought stress. In contrast, Scenario 2 reflects an ecologically restored system, where reseeding, soil rehabilitation, and grazing control have enhanced grassland health, root structure, and soil moisture retention. These conditions significantly improve perennial resilience under drought (Standish et al., 2014; Tilman & El Haddi, 1992).

For both scenarios, land cover data before and during a severe drought event are used to estimate changes in total grassland area. The difference in grassland cover between pre- and during-drought conditions in each scenario forms the spatial basis for the ecosystem service valuation.

Finally, the percentages used to simulate drought-induced changes in vegetation cover should be interpreted as ecologically plausible scenario parameters rather than precise empirical estimates. Their purpose is to represent contrasting ecological trajectories between degraded annual-

dominated grasslands and restored perennial-dominated systems and to explore how these trajectories may influence ecosystem service flows under drought conditions. Furthermore, while the specific parameter values are not derived from time-series vegetation datasets, the sensitivity analysis described below evaluates the robustness of the results across a range of alternative parameter assumptions.

Step 6. Estimate the total value of ecosystem services under each scenario.

Applying the selection criteria described above allowed for the extraction of multiple values from various studies for each ecosystem service. The minimum, maximum, and median values from the data sample were estimated for each service. For ecosystem services with only two available valuation records in the ESVD, the median was calculated as the arithmetic mean of the two values. Given the limited sample size, these estimates should be interpreted with caution, and their associated range is reported to reflect potential variability.

To account for functional differences in ecosystem service provision between perennial and annual grasslands, this study incorporates a series of adjustment factors applied to the median per-hectare values derived from the ESVD (Table 1). These adjustments reflect the ecological reality that perennial grasses typically provide higher levels of services (e.g., regulating) due to their deeper root systems, longer growing periods, and greater biomass retention. For instance, perennial systems sequester more carbon and regulate water flows more effectively than annual-dominated grasslands (Lal, 2004; Postel & Thompson, 2005). Adjustments ranging from 10 % to 30 % were applied to all ecosystem services to reflect these functional advantages. While provisioning services like food may show smaller differences, more stable forage yields and improved resilience under drought conditions in perennial systems support modest positive adjustments as well (Teague et al., 2011). Cultural and non-use services such as existence values and opportunities for recreation and tourism were also modestly uplifted

Table 1
Adjustment table for ecosystem services by grassland type.

Ecosystem service	Perennial vs. annual difference	Adjustment factor	Reference
Climate regulation	Perennials contribute more due to deeper root systems and longer carbon retention.	30 %	Lal, 2004 and Derner & Schuman, 2007
Existence, bequest values	May be higher in perennials due to greater biodiversity and perceived natural value.	10 %	Mace et al., 2012
Food	Perennials provide more stable, year-round forage; annuals produce faster but less reliable yields.	10 %	Teague et al., 2011
Medicinal resources	More diverse perennial systems may support a wider range of medicinal plants.	15 %	Shanley & Luz, 2003
Opportunities for recreation and tourism	Perennial systems tend to be more scenic and biodiverse, enhancing recreational value.	15 %	Pascual et al., 2012
Raw materials	Perennials yield more durable biomass and fiber products.	20 %	Tilman et al., 2006
Regulation of water flows	Perennials regulate flows better by enhancing infiltration and reducing runoff.	30 %	Postel & Thompson, 2005
Waste treatment	Perennials filter runoff and retain nutrients more effectively.	25 %	Brauman et al., 2007
Water	Perennials enhance water retention and reduce evaporation better than annuals.	30 %	Jackson et al., 2005

based on the link between perennial dominance and higher biodiversity (Mace et al., 2012).

These adjustment factors are intended to reflect general functional differences between perennial and annual grassland systems. The percentages applied here should therefore be interpreted as indicative adjustments designed to capture directional differences in ecosystem service provision rather than precise ecological coefficients.

Then, the annual economic value per hectare of each ecosystem service (with an adjusted median for perennials as previously described) was multiplied for the pre- and during-drought area of each type of grassland according to each scenario. Finally, a simplified benefit-cost ratio (BCR) was estimated to explore the potential economic case for grassland restoration. Rather than comparing restoration costs with the total ecosystem service value of restored grasslands, the economic benefit attributable to restoration was defined as the incremental difference between the estimated per-hectare ecosystem service value of perennial and annual grasslands. This approach avoids attributing to the restoration intervention ecosystem service values that would also be provided by the grassland in the absence of restoration.

The BCR was calculated using the following formula:

$$\text{BCR} = \text{Incremental ecosystem service benefit} / \text{Restoration cost}$$

where the incremental ecosystem service benefit represents the difference between the estimated annual per-hectare ecosystem service value of perennial and annual grasslands, and restoration cost represents the annual per-hectare implementation cost of the restoration intervention. A BCR greater than 1 indicates that the estimated incremental ecosystem service benefits exceed implementation costs, while a BCR below 1 indicates that they do not within the annual comparison used here.

The analysis considered the two restoration approaches currently implemented by the GZT, (1) earth bund construction and (2) HLLM. Cost data for both interventions were provided by the GZT and standardized to annual costs per hectare to ensure comparability with the annual ecosystem service values. The resulting BCRs should be interpreted as illustrative estimates rather than observed economic returns, as the analysis assumes that the modeled transition toward perennial-dominated grasslands is associated with the restoration intervention and does not empirically estimate the ecological change attributable separately to earth bunds and HLLM.

2.3. Sensitivity analysis

To assess the robustness of the valuation results, a simplified sensitivity analysis was conducted focusing on key parameters that introduce uncertainty in the model. Two parameter groups were tested: (1) the drought-induced loss of annual and perennial grassland cover and (2) the magnitude of the ecosystem service adjustment applied to perennial grasslands. Baseline drought assumptions in the model considered a 70 % loss of annual grasslands during severe drought conditions, while perennial grasslands experienced losses of 20 % under Scenario 1 (annual-dominated systems) and 10 % under Scenario 2 (perennial-dominated systems). To evaluate the sensitivity of the results to these assumptions, drought loss parameters were varied by ± 20 % relative to their baseline values.

In addition, uncertainty related to the adjustment applied to perennial grassland ecosystem service values was tested by varying the estimated per-hectare value of perennial grasslands by ± 10 %. This adjustment reflects the uncertainty associated with functional differences between perennial and annual grassland systems in the provision of regulating ecosystem services.

For each parameter combination, ecosystem service values during drought conditions were recalculated for both vegetation scenarios. The analysis therefore generated a range of ecosystem service values under alternative drought severity and ecosystem service valuation assumptions, allowing the robustness of the comparative results between

scenarios to be evaluated.

Key limitations.

It is important to highlight the main limitations of the method used to conduct the economic valuation of ecosystem services from grasslands. First, the estimated value of each ecosystem service depends on several factors that can significantly alter the result, such as the number of estimates drawn from the database that was used and the quality of the data. Regarding the number of estimates, due to our prioritization of studies from Kenya and, more broadly, eastern Africa, some ecosystem services were represented by only one or two estimates. The resulting per-hectare values for these services should therefore be interpreted with particular caution, as they are based on a limited evidence base and may be more sensitive to individual study estimates. In addition, when estimating the total value of the ecosystem, it depends on the number of ecosystem services evaluated. Second, the total values represent the potential supply of ecosystem services, since it is assumed that the entire extent of the ecosystem provides in equal magnitude all the ecosystem services. This does not occur in reality due to the particular biophysical characteristics of the natural capital throughout its extent, as well as the location and demand of the beneficiaries. In order to have a more exact value that simulates the demand for services, more complex value transfer methods can be applied, such as a transfer modified by expert opinion (Hernández-Blanco et al., 2021), a transfer modified by spatial modeling, or transfer function meta-regression analysis (Liu et al., 2022). Ideally, primary valuation studies should be the preferred approach whenever feasible.

A third key limitation of the economic valuation lies in the inherent uncertainty associated with the use of value transfer methods, which do not account for site-specific biophysical or socioeconomic differences between the study and policy sites. To partially address this, the range of economic values found in the literature for each ecosystem service was reported, including the minimum and maximum values. While such range reporting does not offer a formal confidence interval, it provides a basic indication of variability. Moreover, existing literature suggests that simple unit value transfers may yield transfer errors averaging between 40 % and 70 %, and in some cases exceeding 100 %, depending on the heterogeneity between source and target contexts (Rosenberger & Stanley, 2006). These factors underscore the need for cautious interpretation of the results and highlight the value of future efforts to calibrate values through primary data collection or locally adjusted transfer functions.

A fourth limitation is related to the constancy of ecosystem service value over time. The ecosystem service values are treated as static over the time frame of the drought impact assessment. This assumes no significant market, policy, ecological or climate-driven changes affecting ecosystem service valuation during the period considered, which simplifies the analysis but may underrepresent dynamic economic or ecological responses. For example, due to the limited scope of the study, the potential effects of the invasive alien plant *P. juliflora* have been excluded. Fifth, there are key assumptions in the effectiveness of restoration that will have an impact on the economic valuation. The post-restoration resilience of perennials in Scenario 2 is assumed to result from effective ecological restoration interventions, such as reseeding with native species, improved grazing management, and soil stabilization. The success of such efforts will vary in practice.

Another limitation of the study is that the impact of droughts is considered uniform. Drought-related losses are estimated as proportional reductions in grassland area based on vegetation type. It is assumed that within each vegetation class (annual or perennial), the impact of drought is spatially uniform, although drought effects may be patchy due to soil variability, topography, or land use intensity. Finally, the proportions of annual and perennial grasses under each scenario are derived from expert-informed, ecologically plausible conditions based on known responses to restoration and degradation. These assumptions reflect not only species composition but also ecosystem structure, rooting depth, and ground cover.

Given these uncertainties, the monetary estimates presented in this study should be interpreted as indicative approximations illustrating the potential magnitude of ecosystem service changes under alternative grassland trajectories rather than precise economic valuations.

3. Results and discussion

In terms of the area of the ecosystem that was valued, the analysis used a total area of grasslands of 371,431 ha, according to the study area delimited by the GZT as their primary zone of interest. Grasslands area represents 29 % of the total study area, followed by shrubland (50 %) and forest and woodland (17 %). It is also important to note that these categories of ecosystems do not exist in a homogeneous way throughout the landscape, but are in heterogenous arrangements with complex ecological dynamics that maintain the health of the entire system and the related provision of ecosystem services to local communities (Hernández-Blanco et al., 2022).

Regarding the values that were extracted from the ESVD, the number of studies that were found for each ecosystem service varied significantly (Fig. 3). 43 % and 38 % of the values extracted are for food and raw materials respectively. The rest of ecosystem services have a similar distribution of values used for the economic valuation, ranging between 1–4 % of the total. Furthermore, the ecosystem services of medicinal resources and water have only 1 estimate each, and existence and bequest values and waste treatment have only 2 estimates each, and therefore their value should be considered with caution. Nevertheless, they are probably an underestimate of their real value.

In terms of the median annual value per hectare, in the case of annual grasses (i.e., values as extracted from the ESVD), food has the highest value (\$824 ha⁻¹year⁻¹), representing 61 % of the total value of ecosystem services. Since food was also the service that had the highest number of estimates, this value has a reasonably high level of certainty. Climate regulation is the second ecosystem service with the highest value (\$511 ha⁻¹year⁻¹), but unlike food, this value is based on three estimates. The total annual value per hectare of annual grasses is \$1359 ha⁻¹year⁻¹, and therefore food and climate regulation represent almost the entire total value (99 %) of ecosystem services provided by these

ecosystems (Table 2, Fig. 4). In the case of the median values of perennials of \$1599 ha⁻¹ year⁻¹ (which as explained in the methods section is a modified value from the median values extracted from the ESVD based on an adjusted percentage), food and climate regulation still cover almost the entire total value (98 %) of their ecosystem services, despite the adjustment percentages applied to vary between these two services.

The total annual economic value per hectare of grasslands estimated under both scenarios is in the same order of magnitude from recent estimates for this ecosystem, such as the one conducted by Liu et al. (2022) where they did a global *meta*-analysis on the economic value of grasslands ecosystem services using 134 studies, with 746 value estimates in total. The authors note the relatively low quantity of studies conducted in Africa (only 8 % of all the assessed studies), similar to the findings and challenges of the present study. The total annual value per hectare estimated by Liu et al. (2022) for tropical grasslands is \$5467. Although this is higher than the estimates for both annual and perennial

Table 2

Annual values per hectare for all ecosystem services assessed. Refer to the Supplementary Material for the complete list of studies from which the economic values were derived.

Ecosystem service	# of estimates	Min	Max	Median annual	Median perennials
Climate regulation	3	473	1227	511	665
Existence, bequest values	2	0.05	0.15	0.10	0.11
Food	39	62	1594	824	907
Medicinal resources	1			1	1
Opportunities for recreation and tourism	4	0.03	0.26	0.11	0.13
Raw materials	35	1	642	20	23
Regulation of water flows	4	1	26	1	2
Waste treatment	2	0.14	0.18	0.16	0.20
Water	1			1	1
Total	91	536	3489	1359	1599

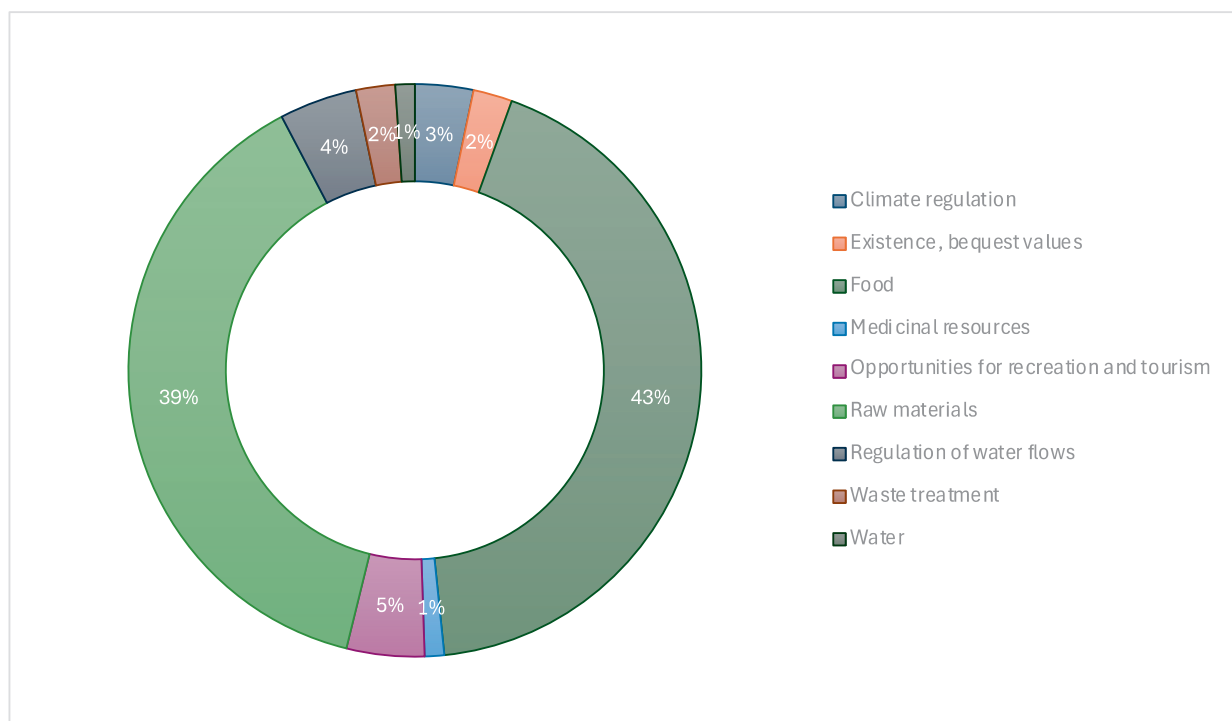


Fig. 3. Proportional distribution of the number of values extracted from the ESVD.

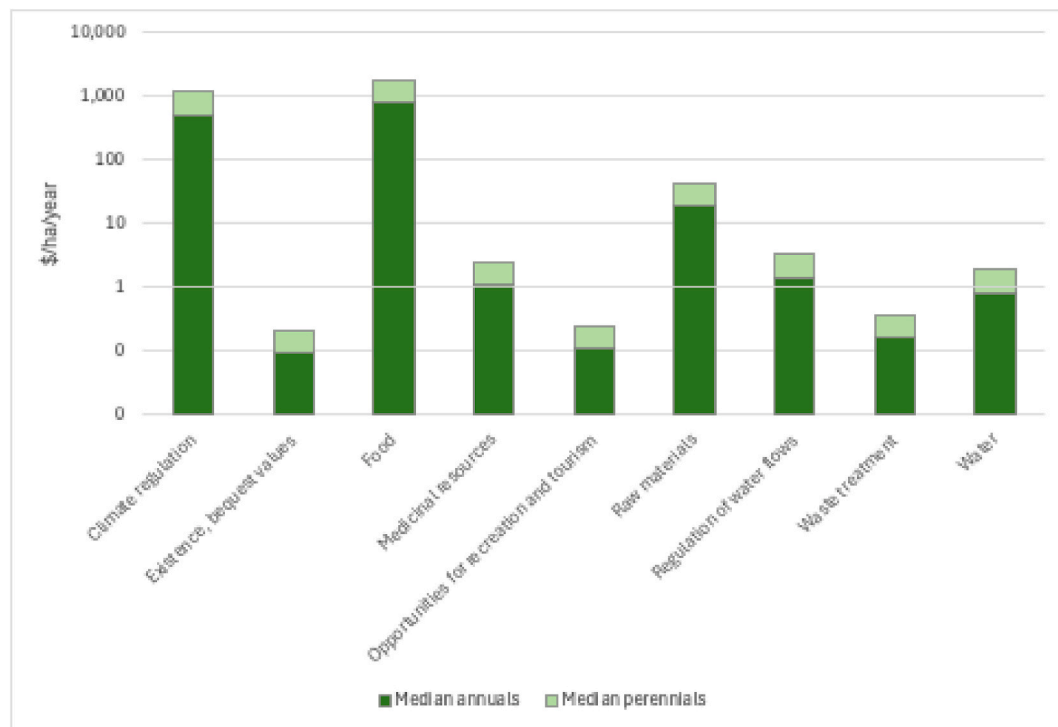


Fig. 4. Values (log) of all ecosystem services assessed for both annual and perennial grasslands.

grasslands in this study, the difference may be explained by purchasing power parity adjustments. Liu et al.'s estimate includes data from countries such as Australia, which have a significantly higher cost of living, and therefore a higher willingness to pay for ecosystem services, ultimately affecting the final value.

Based on the two scenarios used to simulate the resulting area of both types of grassland before and during droughts, in Scenario 1, the annual economic value of grasslands (annual and perennial combined) decreases from an initial value of \$523 million to \$216 million during drought, representing a 60 % loss of economic value derived from the provision of ecosystem services (Table 3). This loss is mostly due to the significant reduction in annual grasses during drought. In Scenario 2, the annual economic value of the ecosystem varies much less, from an

Table 3

Changes in area and economic value of grasslands under two management scenarios.

Scenario	Annual sp	Perennial sp	Total
1. Annual grassland dominance (no restoration)			
Area % prior drought	0.8	0.2	
Area prior drought	297,145	74,286	371,431
Economic value of ES prior drought	403,748,219	118,813,646	522,561,865
Surviving % during drought	0.3	0.8	
Area during drought	89,143	59,429	148,572
Economic value of ES during drought	121,124,466	95,050,917	216,175,383
2. Perennial grassland dominance (restoration)			
Area % prior drought	0.3	0.7	
Area prior drought	111,429	260,002	371,431
Economic value of ES prior drought	151,405,582	415,847,761	567,253,343
Surviving % during drought	0.3	0.9	
Area during drought	33,429	234,002	267,430
Economic value of ES during drought	45,421,675	374,262,985	419,684,660

original estimate of \$567 million to \$420 million during drought, a 16 % reduction, significantly lower than the 60 % reduction in Scenario 1. The difference in the annual economic value during droughts between the two scenarios is \$203 million, illustrating the potential economic benefits of grassland restoration.

The results of this study are broadly consistent with previous research highlighting the economic benefits associated with ecosystem restoration. A growing body of literature has demonstrated that restoring degraded ecosystems can generate substantial gains in ecosystem service provision, including improvements in biomass production, soil fertility, carbon storage, and water regulation. For example, de Groot et al. (2013) showed that ecosystem restoration projects worldwide often generate benefits that exceed restoration costs when the value of ecosystem services is considered. Similarly, Costanza et al. (2014) emphasized that restoring ecosystem functions can significantly increase the economic value of ecosystem services across multiple ecosystem types. In rangeland systems, improvements in vegetation condition have been linked to enhanced provisioning and regulating services.

Moreover, the findings are also consistent with research on dryland and grassland ecosystem dynamics, which highlights the critical role of perennial vegetation in maintaining ecosystem resilience under climatic variability (Reynolds et al., 2007). Studies of rangeland ecosystems have shown that restoration practices that promote perennial vegetation can improve soil stability, increase water infiltration, and enhance forage production (Briske, 2017). These ecological mechanisms help explain why perennial-dominated systems in the scenarios maintain higher ecosystem service values under drought conditions compared with annual-dominated grasslands.

Using data provided by the GZT on the costs of implementing bunds and HLLM for grassland restoration (Tables 4 and 5), the incremental annual ecosystem service benefit associated with the modeled transition from annual to perennial grassland was estimated at approximately \$240.40 ha⁻¹, based on the difference between the estimated values of perennial (\$1599 ha⁻¹yr⁻¹) and annual (\$1359 ha⁻¹yr⁻¹) grasslands. Relative to the annual implementation cost of earth bund restoration (\$751.80 ha⁻¹), this results in a BCR of approximately 0.32, indicating

Table 4
Annual costs of restoration with bunds.

Bunds	
Cost description	Annual cost
Staff time: grassland champions (50 % or 130 working days of year), 16 % or 42 working days –cost of rangelands team time	51,150
Vehicle mileage	5651
Training with VBCs once a year – 32 meetings (out of a total of 48 for foundational + 16 additional) – 50 % of time spend on bunds	4593
Tools (spade, jembe, panga)	1755
Partner meetings + other partner costs – 5.2 meetings (twende, NRT)	373
Seeds	1680
Monitoring (25 % staff time + 50 % of total vehicle/mileage for monitoring)	30,100
Food rations	9791
Team logistics	1667
Additional equipment: laptops, tablets, cameras, handheld GPS (50 % of equipment tagged to rangelands program)	7293
Community meetings with grazing committees + other – 80 = 16 meeting for bunds	4592
Admin cost (percentage of total)(15 %)	17,945
Training with Just DiggIt	215
Rangeland coordinators (3)	775
Total annual cost	137,580
Area under implementation	183
Cost per hectare per year	752

Table 5
Annual costs of restoration with HLLM.

Holistic Land and Livestock Management	
Cost description	Annual cost
Staff: 5 % of grassland champions time, 50 % of rangelands team	79,577
Vehicle mileage – bunching, exposure	16,781
Exposure visits between villages (36 villages – Westgate, Kalama, Meibae total, 8 exposure visits per year)	3445
Staff and county training with Savoury Institute (without admin) – 4 staff, 6 county	25,215
Bunching	40,748
Partner meetings (2.8 days with NRT, 2 program meetings, 16 wet season/dry season meetings – lunch)	7375
Seeds – 300 k	2158
Monitoring	30,100
Quarterly conservancy implementation surveys (32)	2302
Mileage cost tied to quarterly conservancy implementation surveys	1194
Additional equipment: laptops, tablets, cameras, handheld GPS (50 % of equipment tagged to rangelands program), Camping gear, drums	8404
Team logistics/incidentals – food	2848
Admin cost (percentage of total)(15 %)	34,217
Community celebrations (250 k per conservancy)	5383
Rangeland coordinators (3)	2583
Total annual cost	262,330
Area under implementation	35,400
Cost per hectare per year	7

that the estimated incremental ecosystem service benefit does not offset the intervention cost within a single year. For HLLM, with an annual implementation cost of approximately $\$7.41 \text{ ha}^{-1}$, the corresponding BCR is approximately 32.4. The substantial difference between the two BCRs primarily reflects the considerably lower per-hectare implementation cost of HLLM. Therefore, these ratios should be interpreted as illustrative rather than as observed economic returns, since the analysis does not empirically estimate the ecological change attributable separately to each intervention.

It is important to note that in both restoration strategies, the staff-related costs are the highest, approximately 40 % of the total cost in both cases. Monitoring costs are also relatively high, representing 22 % of the costs for bunds, and 11 % for HLLMs.

The sensitivity analysis indicates that the comparative results

between vegetation scenarios remain robust under a range of parameter assumptions (Table 6). Across all tested parameter combinations, perennial-dominated grassland systems consistently maintained higher ecosystem service values during drought conditions than annual-dominated systems. Under the tested parameter ranges, the estimated ecosystem service value during drought varied between \$145.9 million and \$287.4 million for Scenario 1 and between \$353.5 million and \$487.4 million for Scenario 2. The difference between scenarios ranged from \$143.4 million to \$262.8 million, indicating that restoration pathways promoting perennial grassland dominance substantially increase the stability of ecosystem service flows under drought conditions.

Although absolute values change depending on the magnitude of drought impacts and the assumed ecosystem service adjustment factors, the relative ranking of scenarios remains unchanged.

The valuation results may also provide information relevant to the design of financing mechanisms for grassland restoration in northern Kenya. Potential mechanisms include Payments for Ecosystem Services (PES), restoration offsets, carbon or biodiversity finance, and climate adaptation funding, among others. For example, a PES scheme could potentially link payments to ecosystem services enhanced through restoration, such as climate and water regulation, forage provision, or biodiversity conservation. However, the feasibility and design of any such mechanism would require additional analysis beyond the scope of this study, including the identification of beneficiaries and potential funding sources, community governance arrangements, transaction and monitoring costs, and evidence of the ecosystem service changes attributable to restoration.

The economic valuation of grassland ecosystem services under alternative land use scenarios that was conducted in this study provides a framework to inform future investments in restoration in northern Kenya through public, private and blended finance. Moreover, quantifying the benefits provided by intact or restored grasslands highlights the opportunity costs as well (i.e., cost of not perceiving benefits from alternative activities) borne by local communities when these ecosystems are degraded or lost (e.g. due to infrastructure projects). Therefore, comparing baseline and degradation or restoration scenarios can allow policymakers and business leaders to assess the full extent of economic losses, including non-market services that are often excluded from conventional environmental impact assessments. In the specific context of linear infrastructure projects, the economic valuation results can be used to justify compensation payments that reflect not only direct land loss but also the diminished flow of ecosystem services over time.

4. Conclusion

This study highlights the substantial economic value associated with grassland ecosystem services in Northern Kenya and the potential importance of their restoration. Using a value transfer methodology grounded in ecologically relevant data, the annual economic value of ecosystem services was estimated at \$1359 per hectare for annual grasslands and \$1599 per hectare for perennial grasslands. When scaled to the full study area and simulated under drought scenarios, annual-dominated grasslands exhibited a 60 % decline in economic value

Table 6
Sensitivity analysis of ecosystem service values during drought under alternative parameter assumptions.

Scenario	Minimum ecosystem service value (\$)	Maximum ecosystem service value (\$)
Scenario 1: Annual grassland dominance (no restoration)	145,858,996	287,436,606
Scenario 2: Perennial grassland dominance	353,497,735	487,362,201
Difference between scenarios	143,384,443	262,754,478

Note: Values represent the range obtained from sensitivity tests varying drought impact parameters (± 20 %) and perennial ecosystem service values (± 10 %).

during drought, while restored perennial systems declined by only 16 %. This contrast reflects the greater ecological resilience and service continuity typically associated with perennial grass systems, especially in the face of increasing climate variability. The results suggest that investing in grassland restoration has the potential to benefit not only biodiversity and livelihoods, but also the ecosystem services that underpin long-term socio-ecological stability.

The incremental benefit-cost analysis further illustrates how ecosystem service valuation can inform assessments of restoration investments. The estimated annual increase in ecosystem service value associated with perennial rather than annual grasslands was approximately \$240 ha⁻¹. Comparing this incremental benefit with implementation costs resulted in a BCR of approximately 0.32 for earth bunds and 32.4 for HLLM, with the large difference primarily reflecting the substantially lower per-hectare cost of HLLM. As stated before, these estimates should not be interpreted as observed financial returns from either intervention, but as illustrative comparisons based on the estimated difference in ecosystem service values between annual and perennial grasslands. Further empirical research would be required to determine the ecosystem service changes directly attributable to each restoration intervention.

It is important to note that these results are derived from scenario-based ecosystem service valuation and value-transfer methods and therefore represent indicative estimates rather than empirically observed outcomes. Nevertheless, this analysis highlights the potential magnitude of ecosystem service losses associated with grassland degradation and the possible benefits of restoration-oriented management strategies.

CRedit authorship contribution statement

Marcello Hernández-Blanco: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **David Kimiti:** Writing – review & editing, Resources, Conceptualization.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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