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A critical review on restoration of grassland ecosystems: Challenges, strategies and future directions

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Abstract

Grasslands, covering 40 % of global biomes, are crucial for maintaining biological and human life, food security, tourism and climate change mitigation. However, these ecosystems face significant threat from climate change, overgrazing and unsustainable practices like land-use change, leading to declines in biodiversity, productivity and ecosystem resilience. This review aims to identify factors promoting grassland degradation, analyze patterns of degradation and the assessment methods, with a focus on remote sensing and GIS (Geographical Information System) application and evaluate restoration practices and technologies using mechanical, biological and chemical approaches incorporating climate change resilience techniques. Key socio-economic and policy issues challenges include inadequate funding incentives and disjointed governance systems, necessitating stakeholder engagement and sustainable funding. To combat degradation, this study emphasizes the importance of integrating native knowledge from local communities with modern methods and adopting transdisciplinary and climate-resilient approaches for enhanced grassland restoration successes. This study emphasizes on effectively restoring grasslands, improve ecosystem robustness and advance the sustainable development agenda.

Keywords

climate change vulnerability; degradation; grasslands; method of restoration; restoration; remote sensing; socio-economic constraints; sustainable development

Introduction

About 40 % of the world's land area is covered by grasslands; provide habitat for over one billion people and supports diverse ecosystems (1). As managed ecosystems, grasslands play a crucial role in conserving biodiversity, with management practices directly impacting species numbers and ecological processes. Interestingly, research suggests that low-input management such as infrequent moving, can enhance drought resistance in grasslands (2). Indeed, short-term abandonment of productive grasslands may lead to species loss, but these ecosystems are less resilient to management changes compared to species-rich, less-productive grasslands (3). Site heterogeneity, including size and feeding intensity also influences biodiversity level (4). These findings emphasize the need for flexible management approaches to conserve and enhance grassland biodiversity, resource resilience and the ecosystem services.

Site heterogeneity, including herbivore size and feeding intensity, also influences biodiversity levels (4). These findings emphasize the need for flexible management approaches to conserve and enhance grassland biodiversity, resource resilience and ecosystem services. Grassland degradation is a pressing global issue, driven primarily by climate change, overgrazing and human activities (5-7). The deterioration of grasslands has a ripple effect on ecosystem services, including net primary production, carbon stock and soil renewal (Fig. 1). Notably, some areas have demonstrated improved grassland conditions despite ongoing deterioration, highlighting the potential for targeted interventions to prevent decline. To combat degradation, it is essential to enhance recognition of grasslands in global policies; develop standardized indicators of degradation; and improve dissemination of information on restoration practices (8). Given these challenges, employing effective restoration techniques is crucial to revitalize grasslands and facilitate their recovery from ongoing environmental stressors. The grasslands around the word have been listed in Table 1.

This review evaluates the scientific approaches to restoring grasslands, encompassing through sowing and soil management techniques, mechanical, biological and chemical restoration methods. Moreover, this review explores two critical themes, climate change adaptation strategies for grassland restoration and integrating climate-resilient approaches to enhance restoration effectiveness. The review identifies key challenges, including social, economic and policy constraints and emphasizes the importance of cross-sector cooperation, sustainable financing to achieve effective and lasting grassland restoration.

Grassland degradation: Drivers, patterns and assessment

Grassland degradation is a complex process influenced by multiple factors exhibiting varying temporal and spatial patterns globally. In Eastern Inner Mongolia, degradation primarily occurs on gentle slopes (≤5°) and declines with altitude, with human activities and infrastructure playing significant roles (9). Satellite imagery analysis reveals distinct vegetation changes in the Three-River Headwaters Region, Qinghai Province, since the 1970s. Humid meadows and arid steppe ecosystems exhibit different degradation patterns: Humid regions: Grasslands fragment before complete vegetation loss. Arid regions: Vegetation cover declines gradually, leading to desert-like conditions. According to the study based on satellite images showing the vegetation change since the 1970s, the Three-river headwaters region in Qinghai Province has clear differences between humid meadow and arid steppe ecosystems. In the humid regions, grasslands break up before entirely losing vegetation cover, as it happens in arid regions where vegetation cover gradually declines, making way for desert-like conditions. Seven explicitly defined zones demonstrate these differences (10). In Northern Tibet's Naqu region, slight degradation occurred from 2000 to 2011, with central deterioration between 2002 and 2005 and spatial

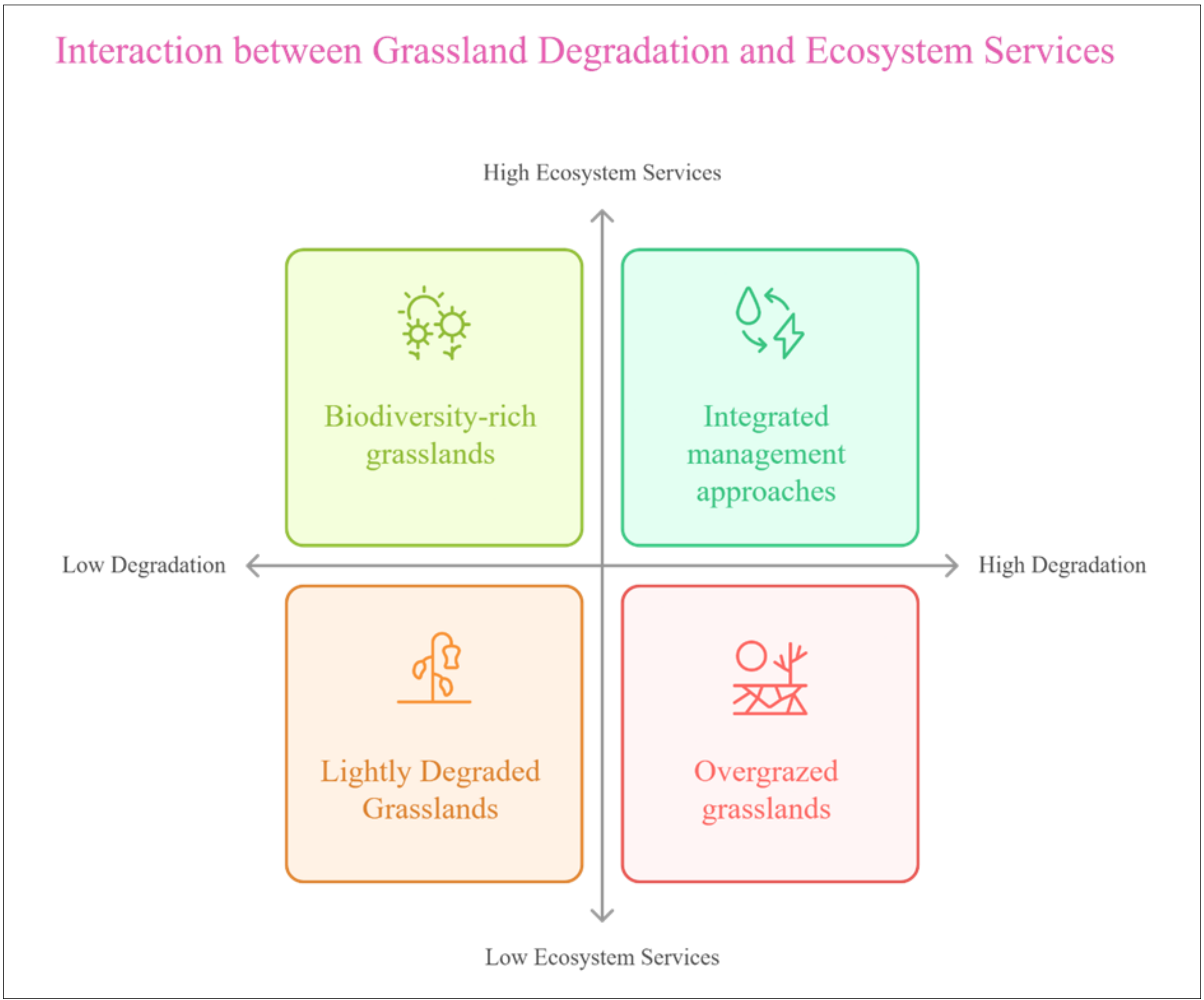

Fig. 1. Interaction between grassland degradation and ecosystem services.

Table 1. Grasslands of the world (54)

Region	Grassland	Location	Key characteristics
North America	Prairies	Great Plains from Canada to Texas	Dominated by grasses like big bluestem; relatively flat terrain
	California grasslands	California's Central Valley	Mediterranean climate; mix of native and introduced species
South America	Pampas	Argentina, Uruguay, Brazil	Fertile plains; temperate climate; important agricultural region
	Llanos	Colombia, Venezuela	Tropical savanna; seasonally flooded; high biodiversity
Eurasia	Steppes	Ukraine through Russia to Mongolia	Vast temperate grasslands; cold winters; semi-arid climate
	Hungarian Puszta	Carpathian Basin	Traditional pastoral landscape; alkaline soils
Africa	Savannas	East and South Africa	Mix of grasses and scattered trees; home to iconic wildlife
	Serengeti Plains	Tanzania, Kenya	Famous for wildlife migrations; acacia-dotted landscape
	Sahel	South of Sahara Desert	Semi-arid transition zone; drought-resistant vegetation
Australia	Mitchell grasslands	Queensland, Northern Territory	Dominated by Mitchell grass; adapted to seasonal rainfall
	Nullarbor Plain	Southern coast	Arid limestone plateau; sparse vegetation
Asia	Mongolian-Manchurian grasslands	Northeastern China, Mongolia	Temperate grasslands; important for nomadic pastoralism
	Terai-Duar savanna	Foothills of Himalayas	Tropical/subtropical grasslands; high biodiversity

differences evident at the county level (11). Multivariate analysis can categorize degradation states based on floristic and biophysical characteristics, guiding restoration efforts. Habitat restoration may require identifying optimal stocking densities Reconstructing ecosystem functions and reestablishing disturbance regimes (e.g., fire, grazing) (12).

Grassland degradation is often the result of multiple factors, both natural and human induced. Overgrazing, urbanization and unsustainable agricultural practices are widely recognized as primary human-driven causes of degradation (7, 13). In China, for example, overgrazing has been identified as a major contributor to degradation. However, research suggests that policy changes, such as privatization of use rights and household enclosures, have also played a significant role. Furthermore, urban expansion and intensive land use have diminished the value of grasslands. Natural factors, including climate change, extreme weather events and altered hydrological cycles, exacerbate these effects. Climate fluctuations often trigger primary degradative changes, while human actions can either exacerbate or mitigate these processes (5, 7, 13). The combined effects of these drivers lead to decline in biomass, decrease in soil nutrient capital, loss of biological assets, decline in ecosystem services and economic impacts (8).

Fig. 2 and Fig. 3 illustrate the natural and anthropogenic drivers of grassland degradation, respectively, while Table 2 consolidates the critical human and natural influences on this biome. To address these issues, it is essential to develop contingency plans that consider ecological, political and socio-economic factors. These plans can help prevent habitat degradation and support rehabilitation efforts (6).

Grassland degradation is a widespread global issue with severe consequences, including reduced vegetation cover and altered composition. Key indicators of grassland degradation include reduced grass height, decreased proportion of forage species, increased proportion of grazing-resistant species and decline in herbage production rate. Spectral data, edaphic factors and spatial developments in grassland cover can be used to map and monitor degradation (14-16). Rangeland degradation is primarily caused by poor grazing practices, vegetation removal for fuel purposes and lack of clear land ownership.

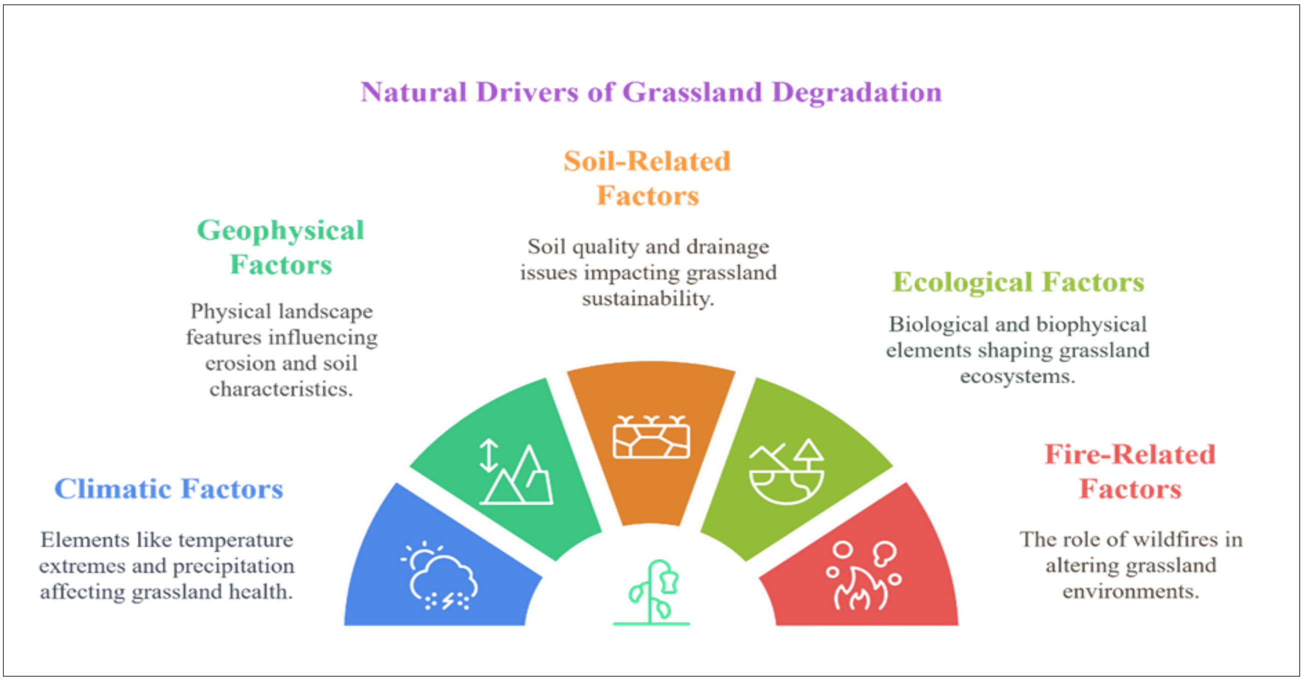

Fig. 2. Natural drivers of grassland degradation.

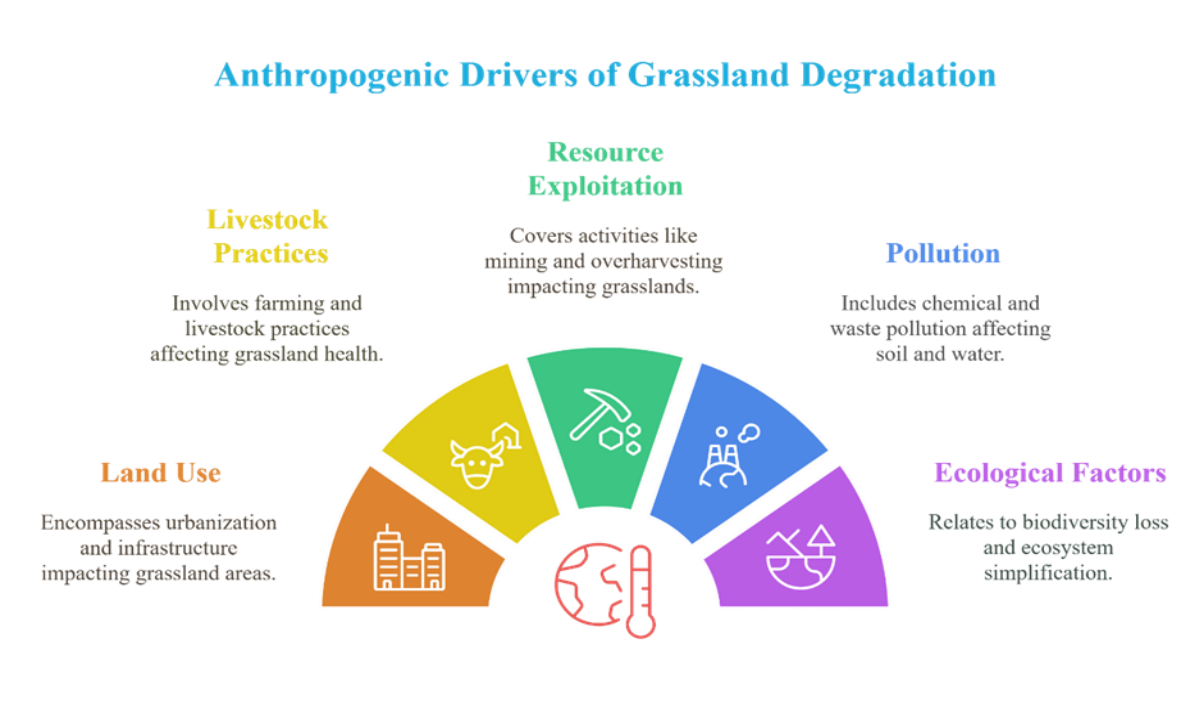

Fig. 3. Anthropogenic drivers of grassland degradation.

Table 2. Drivers and indicators of grassland degradation

Driver/Indicator	Details	Reference
Overgrazing	Major driver, especially in areas like China	(7)
Urbanization	Reduces grassland cover and biodiversity	(13)
Soil nutrient loss	Decline in soil fertility and biological assets	(8)
Remote sensing applications	Utilized for assessing degradation and vegetation changes	(19)
Grazing-resistant species	Increased proportion indicates grassland degradation	(14)

To address these issues, management solutions focus on mitigation and rehabilitation measures. However, rehabilitation is particularly challenging due to the high level of degradation (17). Effective management and conservation of grasslands require a comprehensive understanding of these indicators, processes and solutions. In today's rapidly changing global environment, remote sensing and GIS technologies have become essential tools for assessing grassland degradation. These technologies offer several advantages such as rapid assessment capabilities, relatively low costs and ability to cover large areas (18, 19). Remote sensing and GIS technologies enable the evaluation of livestock distribution, desertification processes and vegetation species abundance, which are critical indicators of degradation (20, 21).

Research has shown that combining remote sensing data with digital elevation models and ground data enhances the accuracy of these assessments (19). Studies in northern China have demonstrated the effectiveness of these tools in identifying suitable areas for agricultural purposes, monitoring desertification processes (22). These technologies facilitate are degradation assessment, rangeland analysis and informed intervention strategies (23). By leveraging up-to-date spatial data and advanced data processing techniques, remote sensing and GIS technologies play a vital role in effective grassland management and restoration (21, 24).

Restoration techniques: Combining the past with present and future

Basically, grassland rehabilitation is an important task to maintain a high level of biodiversity and functions of ecosystems, but it has numerous problems. It is therefore crucial to understand drivers and patterns that mesh within grassland degradation since it forms an important framework for adaptation when designing restoration solutions for the ecosystem. During 18-30 years of ecological restoration from disintegration of agroforestry systems, topsoil removal and seed addition strategies have demonstrated the capacity of plant and soil biota to achieve diverse communities of established networks, though differing from targeted grasslands. Nevertheless, species richness recovery mostly precedes functional recovery, let alone the requirement for post-restoration management to eliminate limitation factors (25). These include seed and site constraints; long-term biological invasions control and integrating global and local restoration objectives (26). Other risks include climate change in restored areas and knowledge gaps in relationships between restoration strategies and grassland types in particular areas and the inability to guarantee the long-term sustainability of restoration as a long-term strategy. To meet these challenges, a means of the existence of a restoration approach to the implementation of restoration measures, site conditions and broad social context is needed for successful multifunctional grassland restoration, which is a vital element of the future conservation and sequestration of carbon (27).

The possible techniques of the grassland restoration include mechanical, biological and chemical techniques as mentioned in Table 3. Mechanical treatments include tilling, mowing and overstory removal, which are some of the mechanical methods that help to enhance native seedling density and understory biomass (28, 29). Biological methods include direct seeding, transplanting of mature plants or topsoil from the donor sites (30). Chemical strategies capture herbicides such as imazapyr and glyphosate to prevent invasive species (28, 31). The addition or the immobilization of nitrogen appears to affect the pattern of restoration (28). Prescribed fire can be used in conjunction with other treatments to maximize restoration potential (29). Therefore, the restoration strategies applied depends on the target species, community type and goal. First, continued conservation of the high-quality grasslands is cheaper than the restoration of degraded ones. The effective post-restoration management is critical to maintaining long operating periods and it has been suggested that managers should be to adopt a contingency approach to management (30, 31).

Biological and mechanical treatments integrated with herbicide application will be useful for grassland rehabilitation and control of invasive plants (32). Experimental clipping of the invasive woody plant *P. juliflora* has improved the restoration of native herbaceous plant assemblages, however for long-term restoration of these native herbaceous plants may require continuous management intervention to ensure sustained ecological balance (33). Appropriate management goals for restoration programs are expected to respect initial site conditions, how the restoration measures are applied and effects on the social environment for sustainable future outcomes (27). Topsoil removal and then seeding have been effective in the recovery of both the above- and below-ground functional and phylogenetic diversity and ecosystem services, as the restored grasslands have provided the target species and phylogenetic structure within eighteen years (34). Network analyses could also be used for the assessment of current development of ecosystems' connections and the overall restoration (34). These integrated strategies indicate potential courses of action towards site-specific grassland restoration in the light of invasive species and climatic variability.

Table 3. Overview of grassland restoration techniques: Methods, purposes, benefits and challenges

Category	Technique	Purpose/Focus	Benefits	Challenges	References
Mechanical	**Tilling and mowing**	Removing invasive species and preparing soil for reseeding	Improves seed germination; reduces competition from invasive plants	Risk of soil disturbance; high labour and equipment costs	(28)
	Erosion control	Use of terraces, silt fences and check dams to stabilize soil	Prevents soil loss; maintains moisture	Long-term maintenance and potential failure under extreme weather	
	Overstory reduction	Removing overstory vegetation to enhance native seedling density and understory biomass	Promotes native plant growth; reduces shade impact	May require repeated interventions; potential harm to non-target vegetation	(29)
Biological	**Native species reintroduction**	Introducing native grass species and functional groups (C4, C3 grasses, nitrogen-fixing plants)	Enhances biodiversity; improves ecosystem resilience	Limited availability of native seeds; species establishment may be uncertain	(30)
	Topsoil and mature plant transfer	Transferring mature plants or topsoil from donor sites to degraded areas	Restores soil microbial communities; promotes natural regeneration	Requires healthy donor sites; expensive and labor-intensive	
Chemical	**Controlled fertilization**	Use of slow-release fertilizers or nano-fertilizers to improve soil nutrients	Enhances soil fertility; supports vegetation growth	Risk of nutrient leaching or overapplication	(31)
	Targeted herbicide application	Managing invasive species using herbicides like imazapic and glyphosate	Reduces invasive species competition	Potential harm to non-target species; ecological risks from chemical residues	(28,31)
	Nitrogen manipulation	Addition or immobilization of nitrogen to influence restoration outcomes	Alters competitive dynamics between invasive and native species	Requires precise application to avoid ecological imbalance	(28)
Integrated	**Combined restoration methods**	Tailoring mechanical, biological and chemical techniques based on site-specific conditions	Maximizes effectiveness; allows flexible adaptation to ecosystem needs	Requires thorough ecological assessment; implementation complexity	(27,32)
	Prescribed fire	Using fire in combination with other techniques for vegetation management	Enhances seed germination; reduces invasive species	Risk of uncontrolled fires; requires specialized training	(29)
Innovative	**Green hay transfer**	Using donor site hay to seed degraded areas	Promotes natural biodiversity transfer; cost-effective	Requires healthy donor sites; seasonal limitations	(37)
	Wide-strip overseeding	Increasing seed establishment and improving hay yield and feed quality	Enhances productivity and forage quality	Requires extensive land preparation; challenges in managing large plots	(35)
	Topsoil removal with seeding	Removing topsoil to reduce weed seed banks, followed by seed addition	Restores biodiversity and ecosystem functioning	Cost-intensive; may lead to soil erosion without careful implementation	(34)

Some peculiarities of grassland restoration, including seed and site limitations, can be considered the key tech-driven questions (26). Overseeding with a wide strip has potentialities. in increasing hay yields and feed quality on dairy farms (35). New technologies related to seed production and vegetative propagation include in vitro rooting and high-density stem cutting nursery technology and de-fluffing technology for different grasses (36). In the degraded Mediterranean dry grasslands, the capability to restore the area is limited by the weak seed bank and the low occurrence of perennial plants. Some of the restoration practices include sowing, transplanting, hay and soil transfer and the best practices are dependent on the climate condition of a given area and should be used in combination with appropriate grazing or fire regimes (37). More studies are required to enhance the understanding of restoration. processes, especially in dryland and (sub) tropical ecosystems, as well as to advance the generation of climate-resilient restoration frameworks (26).

Climate-resilient strategies in grassland restoration

Restoring grassland is an ordeal. complicated much by climate change factors. Consequently, as climate change intensifies, it is increasingly relevant to introduce climate-proof approaches that will enable sustained success in promoting grassland conservation, including where environmental conditions are likely to change. Analyses of climate models show significant declines in suitable homeland for many grassland plants in the future and thus management planning should be future proofed for long-term persistence (38). They are important for food and for water security and climate change adaptation and there is scope for carbon storage and sequestration therein (39). Species-rich grasslands are still very limited, though studies on grassland restoration have revealed that grassland conservation is beneficial in enhancing vegetation cover and reducing greenhouse gas emissions in the Tibetan Plateau region (40). However, the changes in these inputs may dramatically impact restoration outcomes. A study conducted in California reveals that the mature bunchgrasses with increased precipitation accrued benefits while seedling establishment was inhibited by the thickening of the stands of exotic species (41). These results indicate that the strategies based on replanting, the similar older age, may be less sensitive to the climate fluctuations; the plants can withstand almost any climatic regime and compete with invaders more effectively.

Climate-resilient approaches for the rehabilitation of grassland ecosystems as global warming tightens its grip on Earth through disastrous extreme weather events are essential. The advanced use of adaptive multi-paddock grazing, agrivoltaics, agroforestry and enhanced weathering are promising practices for higher productivity, sustainability and higher rates of carbon capture in grassland ecosystems (42). Species Distribution models might help to identify climate resilient plant species for seed mixes for the site and the ranges of warm-season grasses, forbs and legumes are similar within these functional groups (43). Persistent seed banks can maintain restoration in the wetlands as well as in frequently disturbed ecosystem types, while the active restoration by means of seed addition can be more effective in less disturbance-adapted habitats (44). Each of these strategies as shown in Fig. 4, contributes to building climate-adaptive grassland systems that are productive, resilient and pro-climate mitigation. The key restoration techniques and climate-resilient strategies that align with the goals of promoting sustainability and climate adaptation in grassland ecosystems are provided in Table 4.

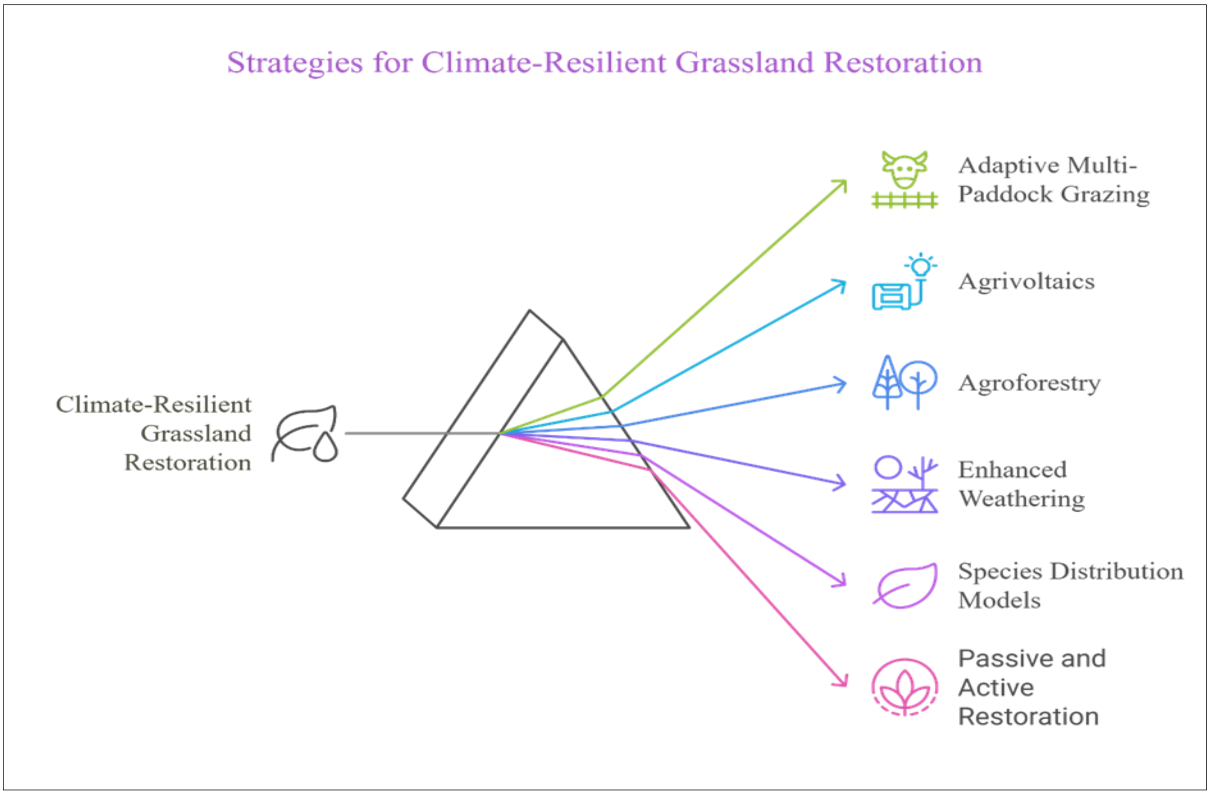

Fig. 4. Strategies for climate-resilient grassland degradation.

Table 4. Restoration techniques and climate-resilient strategies

Technique/Strategy	Details	Reference
Carbon sequestration potential	Grasslands contribute to climate mitigation	(39)
Dual and multi-paddock grazing	Improves productivity and sustainability	(42)
Persistent seed banks	Effective in wetland and disturbed ecosystems	(44)
Weather-based management	Basing restoration on climate conditions	(46)
Heatwave resilience	Grasslands show recovery in primary productivity after drought	(48)

Studies highlight the interdependency of climate extremes and the process of grassland restoration efforts. Despite some favourable effects of grazing for grassland, there are some deleterious effects, such as extreme precipitation and temperature events, that erode the benefits and stress those valuable endemic species (45). Basing rangeland revegetation on the weather conditions, historical, seasonal and climate might be useful in restoring the vegetation in the semi-arid rangelands (46). Threats such as halting the use of fertilizers in farmland will enhance the resistance of carbon fluxes to drought, but this will reduce crop yields (47). Experimental studies have revealed that, although grasslands are heat wave resilient, extreme drought can affect ANPP (Above-ground Net Primary Productivity) and species assemblages. But it has been shown that primary productivity can bounce back after the drought, affirming ecosystem hardness (48). These observations should be incorporated into planning and management of grassland restoration efforts with a focus on extremes of climate.

Socio-economic effects in grassland management

Social and economic factors play a crucial role in grassland restoration and its outcomes. Economic incentives, policy frameworks and local community engagement are essential for maintaining stakeholders' interest in sustainable grassland management. While ecological restoration methods offer ways to prevent and restore damage, their success is closely tied to socio-economic factors and stakeholder concerns. Research suggests that grassland degradation is often the result of complex interactions between abiotic and biotic factors (49). A recent survey found that farmers' willingness to maintain the restored grasslands is influenced by economic returns, such as agri-environmental payments and political support from local communities (50). To evaluate the effectiveness of restoration policies, it's essential to consider, the improvements in stakeholders' attitudes toward restoration and changes in land management practices (51). Integrating socio-economic studies into restoration practices is critical for minimizing conflicts and promoting participatory restoration processes (52). Ensuring long-term sustainability in restoration projects requires consideration of the ecological and social context, including farm economy, authority support and effective management practices (50).

Grassland degradation is a complex issue with multiple socio-economic and natural causes, varying across time and space (49). To address this, a comprehensive understanding of the socio-economic factors influencing grassland restoration is essential (Fig. 5, Table 5). A social-ecological system approach is necessary to consider stakeholder attitudes, governance systems and policies in restoration initiatives (51). Despite their importance for global biodiversity and ecosystem services, grasslands have received limited attention in sustainable development policies (8). To combat degradation and promote sustainable development, strategies such as enhancing policy recognition, developing common protocols for degradation indicators, improving knowledge exchange mechanisms (8) are crucial. However, Ecological Restoration Projects (ERPs) interact with various policies, complicating their effects on social-ecological systems (53). In northern China's agro-pastoral ecotone region, grass-based livestock husbandry and local economic development had a more significant impact on rural income than ERPs (53). Understanding these complex relationships is vital for policymaking and balancing competing stakeholder demands in grassland restoration.

Challenges and future directions in grassland restoration

Grassland restoration poses significant challenges due to the interplay of ecological, economic and climatic factors. Key obstacles include seed and site limitations (restoring stressed ecosystems, particularly those with poor soils and low native seed supply, remains a challenge) and invasive species and altered disturbance regimes (these factors can hinder ecosystem recovery or trigger unintended ecosystem shifts). To overcome these challenges, strategies such as seedling distribution, targeted soil amendments and climate-resilient species selection. However, long-term sustainability is often hindered by short-term knowledge gaps, particularly in dryland and (sub) tropical grassland ecosystems. Addressing these knowledge deficits is crucial for developing efficient, site-specific restoration plans.

Table 5. Socio-economic factors influencing grassland restoration

Factor	Details	Reference
Economic incentives	Payments and subsidies encourage sustainable practices	(50)
Policy frameworks	Essential for stakeholder engagement and restoration success	(51)
Local community involvement	Improves long-term restoration outcomes	(52)
Agri-environmental payments	Key to farmer participation and grassland sustainability	(49)
Grassland-based livelihoods	Enhance rural incomes and reduce dependence on non-sustainable practices	(53)

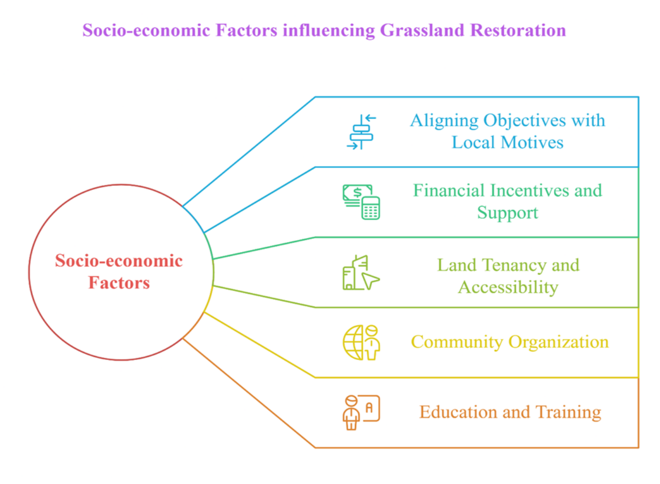

Fig. 5. Socio-economic factors influencing grassland degradation.

Socio-economic and policy constraints pose significant threats to African firms and governments when addressing equipment needs for restoration efforts. Specifically limited financial incentives, ambiguous land tenure regimes and poor public participation can undermine restoration processes. Effective restoration schemes rely on the engagement and stewardship of local communities, as evident in reforestation efforts. However, integrating grassland restoration into broader sustainable development frameworks has been inconsistent, lacking coherence, comprehensiveness and resources. To overcome these challenges multi-stakeholder engagement must increase, policy understanding and acceptance of grasslands' ecological value must improve and sustainable financing mechanisms must be established. Emerging restoration strategies should incorporate adaptive management measures, considering climate change impacts on species distribution and meteorological conditions for revegetation. By addressing these socio-economic, policy and environmental factors, effective grassland restoration can be achieved.

Advancing the grassland restoration agenda requires an integrated approach that combines conventional science, indigenous wisdom and modern technologies. Tools like remote sensing, GIS and network analysis offer enhanced precision and scalability for restoration efforts. To capture the complexities of grassland rehabilitation, scholarship must integrate environmental, social and economic contexts. This holistic approach can balance biodiversity conservation with socio-economic benefits, effectively managing large-scale degradation. This paper proposes that innovative strategies, stakeholder engagement and adaptive planning can enhance the restoration process. By adopting this approach, grassland restoration can significantly contribute to global sustainability and climate change mitigation, ultimately supporting the attainment of these critical goals.

Conclusion

Conserving and rehabilitating grasslands is crucial for maintaining biological diversity, ecosystem functions and service delivery, as well as sustaining human livelihoods amidst land degradation and climate change. While challenges like seed and site limitations, invasive species and socio-economic factors persist, advances in ecological science and new methodological approaches offer opportunities for effective restoration. Mechanochemical-biological strategies and adaptive management practices can provide site-specific solutions and sustainable results. Stakeholder engagement, policy recognition and integration of indigenous knowledge are essential for scaling up restoration efforts and ensuring socio-economic relevance. Emerging technologies like remote sensing, GIS systems and climate modelling can enhance the accuracy and efficiency of restoration planning and monitoring. This paper highlights the significance of grasslands in carbon storage, food production and climate change mitigation, as well as sustainable development. To address the complex challenges facing grasslands, an integrated solution is needed, leveraging advanced tools and effective policies to overcome current obstacles. By combining these strategies and coordinating with stakeholders, grassland restoration efforts can rise to the challenges ahead, ensuring a sustainable and resilient future for these vital ecosystems.

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Authors' contributions

AH, KB and SM chose the review topic and its outline. HP corrected my grass restoration-related points. TM contributed ideas related to the topic and drafted the manuscript. The figures are all made by AH. RR and RM helped with the overall correction of the manuscript. All other authors RR and RM read and approved the final manuscript.

Compliance with ethical standards

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