Governance Levers Matrix for Grassland Biodiversity and Ecosystem Services

Aleena*[1], Maryam Saleem[2], Ghazala yasmeen[3] ,Mushtaq Ahmad*[4]

1 State Key Laboratory of Herbage Improvement and Grassland Agro-ecosystems, College of Ecology, Lanzhou University, Lanzhou 730000 China

2 Centre of biotechnology and microbiology (COBM), University of Peshawar, Pakistan

3 Laboratory of Plant Ecology and Conservation Qauid-i- Azam University Islambad Pakistan

Corresponding Authors: Aleena* and Mushtaq Ahmad*,

Abstract

Grasslands are indispensable biomes providing critical ecosystem services, yet their ecological integrity is increasingly threatened. Despite extensive but fragmented research on services, biodiversity, and management drivers, a translational framework to guide governance remains elusive. This review introduces the Governance Levers Matrix, a novel, integrative decision-support framework designed to bridge this gap. We synthesize knowledge across three domains ecosystem services, biodiversity indicators, and governance mechanisms into a three-dimensional matrix linking desired outcomes (services), measurable states (indicators), and actionable interventions (levers). Our analysis reveals that effective stewardship requires multi-scale coordination, as field-level management is often constrained by landscape context and policy architecture. Key insights include the explicit mapping of trade-offs (e.g., forage production vs. species richness) and synergies (e.g., biodiversity enhancing carbon sequestration), and the critical role of collective action. We demonstrate that prevailing policy instruments, such as agri-environment schemes, frequently underperform by neglecting this multi-scale logic. The matrix thus provides a structured tool for diagnosing governance failures, designing targeted interventions, and navigating complex socio-ecological trade-offs. We conclude with targeted recommendations for policy reform including a shift to outcome-based incentives and landscape-scale coordination and a research agenda focused on quantifying matrix relationships and integrating climate adaptation. This framework advances grassland science from descriptive ecology toward prescriptive, evidence-based governance.

Keywords: Grassland governance; Ecosystem services; Biodiversity indicators; Multi-scale management; Policy integration; Socio-ecological systems.

1. Introduction

1.1 Research context

Grasslands, encompassing vital biomes from the fertile prairies of North America to the biodiverse savannas of Africa, deliver indispensable ecosystem services from carbon sequestration to pollination—that form the ecological foundation of sustainable agriculture and climate resilience (Bengtsson et al. 2019, Bardgett et al. 2021). Yet these systems face unprecedented degradation from land-use intensification and climate change, threatening both biodiversity and human livelihoods (Pandit et al. 2018). This degradation creates an urgent need for governance frameworks that can translate ecological knowledge into actionable strategies for conservation and sustainable management.

The scientific response to this need, however, has remained fragmented across three distinct research paradigms. First, ecosystem service research has developed sophisticated frameworks for quantifying and valuing grassland contributions to human well-being (Zhao et al. 2020, Hernández-Blanco et al. 2022). Second, biodiversity science has established comprehensive indicators—from taxonomic richness to functional traits—that capture different dimensions of ecological communities (Dalongeville et al. 2022, Hou et al. 2023). Third, ecological research has elucidated the complex drivers—including grazing regimes, nutrient enrichment, and climate variables—that shape grassland composition and structure (Wu et al. 2023, Lu 2024). While each paradigm has generated substantial insights, their continued isolation represents what (Mohamed and Systems 2025) identified as a fundamental barrier to implementing biodiversity-based solutions: the "science-policy-practice gap" in ecosystem management.

This gap manifests as a critical disconnection between understanding ecological patterns and implementing effective interventions. While recent syntheses have called for more integrated approaches (Bengtsson et al. 2019), most frameworks remain either theoretical or narrowly focused, failing to provide the specific, operational guidance needed by land managers and policymakers. Consequently, there exists a pressing need for a novel synthesis that explicitly bridges these domains—transforming passive observations of correlation into active strategies for ecological stewardship (Kremen and Merenlender 2018).

This review addresses that need by introducing the Governance Levers Matrix (GLM), a conceptual framework designed to integrate knowledge across these three research traditions into a decision-support tool. The GLM operationalizes the concept of "ecological leverage points" identifiable factors within socio-ecological systems where targeted interventions can produce disproportionate benefits for biodiversity and ecosystem services (Kolinjivadi et al. 2015, Koskimäki 2021). We propose that effective grassland governance requires moving beyond generic principles to specific, evidence-based mappings between (1) manageable drivers, (2) responsive biodiversity indicators, and (3) targetable ecosystem service outcomes.

Accordingly, this paper has three objectives: First, to synthesize current understanding of how key drivers affect grassland biodiversity across organizational levels. Second, to evaluate which biodiversity indicators show the strongest mechanistic links to priority ecosystem services. Third, to integrate these relationships into the GLM framework, thereby providing a structured approach for identifying strategic intervention points, anticipating trade-offs, and designing synergistic management strategies. Through this synthesis, we aim to advance grassland science from descriptive ecology toward prescriptive stewardship equipping decision-makers with a systematic approach for navigating the complex socio-ecological challenges of the Anthropocene.

2. Methodology

2.1 Literature Synthesis Approach

This review employs a systematic synthesis approach, integrating principles from systematic review methodology with conceptual framework development techniques (Brunton et al. 2020, Schreiber and Cramer 2024). To construct the Governance Levers Matrix, we conducted a comprehensive literature search across the Web of Science, Scopus, and Google Scholar databases. The search strategy was designed to capture the interdisciplinary breadth of knowledge spanning the three foundational domains underpinning the matrix: ecosystem services, biodiversity indicators, and governance mechanisms. The search utilized Boolean operators to combine terms from three conceptual clusters:

(1) Ecosystem Services: (grassland ecosystem services, forage production, carbon sequestration, water regulation and pollination)

(2) Biodiversity Indicators: (plant diversity, species richness, functional traits, phylogenetic diversity and community composition)

(3) Governance & Management: (grassland management, grazing regime, mowing frequency, fertilization, agri-environment schemes and landscape connectivity)

To ensure the review's relevance and rigor, we applied explicit inclusion and exclusion criteria. Included publications were: (1) peer-reviewed articles published between 2000–2025; (2) studies focused on permanent or semi-natural grasslands (established for >5 years); (3) research addressing at least one of the three core domains; and (4) studies providing quantitative data or robust conceptual insights applicable to the matrix framework (Bengtsson et al., 2019). We excluded: (1) studies of arable systems or short-term leys; (2) purely methodological papers without ecological application; and (3) publications with insufficient methodological documentation.

2.2 Framework Development

The Governance Levers Matrix was developed through an iterative, multi-stage process of conceptual modeling and synthesis (Shukla). Its construction is anchored in three complementary theoretical foundations, which collectively provide the scaffolding to link ecological processes with management action. First, Community Assembly Theory offers a mechanistic understanding of how abiotic and biotic filters acting as potential governance levers determine species composition and functional structure at different spatial scales (Feng et al. 2025, Verma et al. 2025). Second, the Ecosystem Service Cascade Model provides a logical pathway tracing the translation of biodiversity and ecosystem functions into final benefits for human well-being, thereby defining the target outcomes of the matrix (Zhang et al. 2022). Third, Multi-Level Governance Theory acknowledges that effective environmental management requires interventions coordinated across institutional, spatial, and temporal scales, informing the matrix's application context (Partelow et al. 2020).

Building upon this theoretical triad, the matrix was structured to explicitly integrate the three-dimensional nature of grassland socio-ecological systems: the ecosystem services dimension (defining desired outcomes), the biodiversity indicator dimension (providing measurable ecological state variables), and the governance lever dimension (identifying actionable intervention points). Each dimension was populated and refined through continuous reference to the synthesized literature, with particular emphasis on mapping documented cause-effect relationships and identifying critical interaction zones where levers, indicators, and services intersect (Assyifa et al. 2025). This structured yet dynamic approach ensures the matrix is both evidence-based and practically applicable for guiding targeted governance strategies.

3. The Governance Levers Matrix Framework

The Governance Levers Matrix represents a three-dimensional conceptual framework designed to integrate ecosystem services, biodiversity indicators, and governance mechanisms into a unified decision-support tool. By aligning desired outcomes (ecosystem services) with measurable ecological states (biodiversity indicators) and actionable intervention points (governance levers), the matrix enables a systematic approach to grassland stewardship. The conceptual architecture of this framework is presented in Figure 1.

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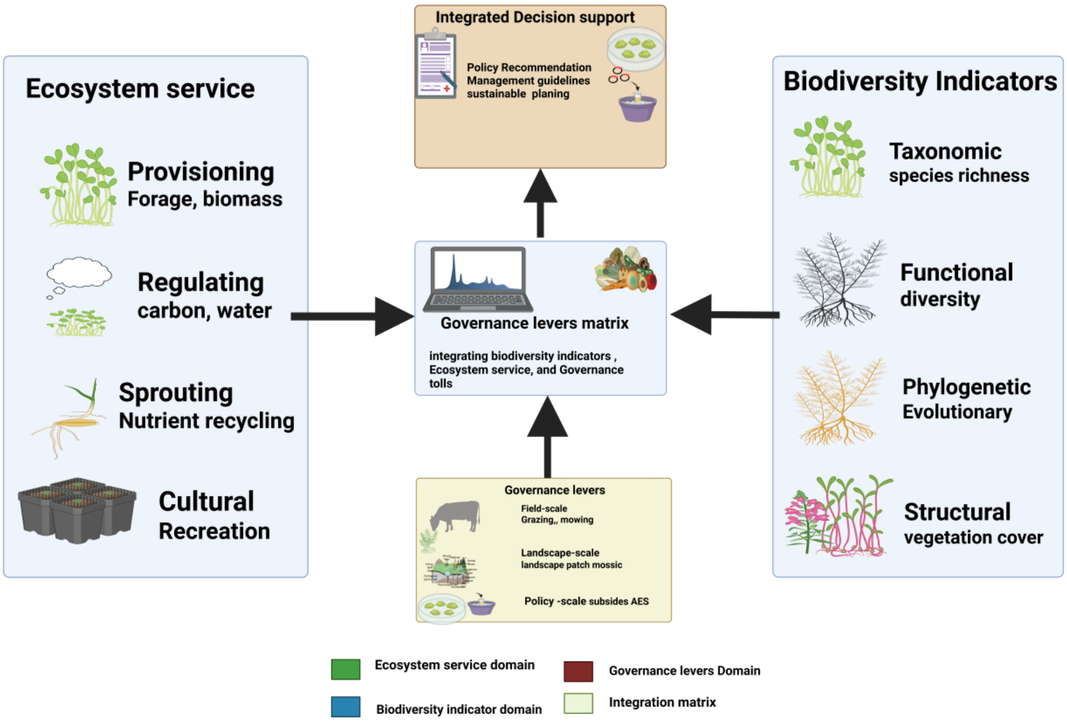

Figure 1. Conceptual diagram of the Governance Levers Matrix showing the three integrated dimensions: Ecosystem Services, Biodiversity Indicators, and Governance Levers. The central integration point synthesizes information from all three dimensions to generate policy recommendations and management guidelines.

3.1 Dimension 1: Ecosystem Services

The ecosystem services dimension of the matrix is organized according to the Millennium Ecosystem Assessment classification, recognizing four categories of services that grasslands provide to human societies. This dimension fundamentally answers the question: What benefits do we want to sustain or enhance?

3.1.1 Provisioning Services: Grasslands provide essential provisioning services, primarily through forage production for livestock grazing and hay-making. The global value of this service is substantial, supporting approximately one billion head of cattle and two billion sheep worldwide (Baumont et al. 2014). Additional provisioning services include biomass for bioenergy, medicinal plants, and genetic resources. Critically, research has demonstrated that biodiversity underpins the reliability of these services, with species-rich communities often exhibiting greater stability in forage production across varying environmental gradients (Sanderson et al. 2004, French and Environment 2017).

3.1.2 Regulating Services: Beyond provisioning, grasslands deliver critical regulating services, including carbon sequestration, water regulation, erosion control, and pollination support. Carbon storage in grassland soils constitutes a significant global sink, with estimates suggesting grasslands store approximately 20% of global soil carbon stocks (Bai and Cotrufo 2022). Water regulation services encompass groundwater recharge, flood mitigation, and water quality improvement via nutrient retention. Furthermore, diverse plant communities directly support pollination services, which benefit both the grassland ecosystem itself and adjacent agricultural systems.

3.1.3 Supporting Services: Supporting services, such as nutrient cycling, soil formation, and primary production, form the ecological foundation for all other service categories. Plant diversity plays a fundamental role in these processes, with diverse communities facilitating more efficient nutrient cycling and conferring greater overall ecosystem stability (Hu et al. 2024). The extensive literature on the biodiversity-ecosystem functioning relationship provides robust evidence that species loss can significantly impair these foundational processes (Correia and Lopes 2023).

3.1.4 Cultural Services: Finally, grasslands provide diverse cultural services, including aesthetic values, recreational opportunities, spiritual significance, and educational value. Traditional grassland landscapes often hold deep cultural meaning for local communities, and the aesthetic value of flower-rich meadows contributes directly to human well-being (Dushkova and Ignatieva 2025). Although less readily quantifiable than provisioning or regulating services, these cultural dimensions are increasingly recognized as vital components of grassland value and conservation justification.

3.2 Dimension 2: Biodiversity Indicators

The biodiversity indicators dimension addresses the question: How do we measure ecological condition and change? Effective biodiversity assessment requires multiple complementary approaches, as no single metric captures all relevant aspects of biodiversity. Consequently, the matrix framework incorporates four categories of indicators, each providing distinct insights into grassland ecological condition.

3.2.1 Taxonomic Diversity: Taxonomic diversity indicators, including species richness, composition, and evenness, provide the most direct measure of biodiversity. Species richness the number of species present remains the most commonly used metric and has been correlated with various ecosystem functions (Blowes et al. 2022). However, this measure alone may not capture critical functional differences between communities, and its relationship to ecosystem services is often context-dependent.

3.2.2 Functional Diversity: To address this limitation, functional diversity indicators capture the range and value of functional traits within a community, offering more direct insights into ecosystem processes and services. Key functional traits for grassland plants include specific leaf area (SLA), leaf dry matter content (LDMC), plant height, and flowering phenology (Fenollosa et al. 2024). Metrics such as functional richness and Rao's quadratic entropy have frequently been shown to predict ecosystem functioning more reliably than taxonomic diversity alone (Liu et al. 2023). Furthermore, community-weighted mean trait values serve as powerful indicators of management effects and predictors of specific ecosystem service delivery ((Sarker et al. 2024).

3.2.3 Phylogenetic Diversity: Phylogenetic diversity measures the evolutionary relationships among species in a community, providing insights into evolutionary history and potential functional redundancy. Communities with high phylogenetic diversity contain species from distantly related lineages, potentially encompassing a broader range of ecological strategies. This diversity has been linked to greater ecosystem stability, suggesting it may provide an "insurance" effect against environmental change (Ross and Sasaki 2024).

3.2.4 Structural Diversity: Structural diversity indicators capture the physical architecture of vegetation, including height, cover, and spatial heterogeneity. These indicators are often directly relevant to service provision, particularly for forage production and habitat quality. Advances in remote sensing have enabled the derivation of spectral diversity as a promising proxy for plant diversity, facilitating assessment at the landscape scale (Van Cleemput et al. 2023).

3.3 Dimension 3: Governance Levers

The governance levers dimension directly tackles the practical question: How can we achieve desired outcomes? Governance levers are defined as the points of intervention through management actions and policy instruments that influence ecosystem services and biodiversity. The matrix framework organizes these levers into three nested scales of action.

3.3.1 Field-Scale Levers: Field-scale levers are management practices directly implemented by land managers within individual grassland parcels. These include grazing management (stocking rate, seasonality, livestock species), which profoundly affects plant community composition (Van Cleemput et al. 2023); fertilization (notably nitrogen application), which typically reduces species richness while boosting productivity (Francksen et al. 2022); and mowing regime (frequency and timing), which influences species composition and recruitment (Liu et al. 2024). While these are the most directly controllable interventions, their effectiveness is constrained by factors operating at broader scales.

3.3.2 Landscape-Scale Levers: Landscape-scale levers operate beyond individual fields and encompass factors like landscape heterogeneity, habitat connectivity, and spatial configuration. Landscape heterogeneity—the diversity of habitat types in the surrounding matrix—directly influences the regional species pool available for colonization (Suárez-Castro et al. 2025). Similarly, habitat connectivity affects species dispersal and gene flow, with critical implications for population persistence (Dalui et al. 2024). These landscape-scale factors act as powerful filters on local plant diversity, determining which species can establish and persist. Crucially, they are often beyond the control of any single land manager, necessitating coordinated action or higher-level policy intervention.

3.3.3 Policy-Scale Levers: Policy-scale levers include the institutional and economic instruments through which societies steer grassland management. Agri-environment schemes (AES) are the primary policy instrument for grassland conservation in many regions, providing payments to farmers for implementing biodiversity-friendly practices (Saba 2025). However, their effectiveness has been variable, with many schemes failing to meet biodiversity objectives. The matrix framework suggests this limited success may stem from a predominant focus on field-scale practices while neglecting landscape-scale constraints. Therefore, policy reforms that incentivize landscape-scale coordination and shift toward outcome-based payments may be essential for improving conservation effectiveness.

4. Driver Interactions and Trade-offs

A fundamental contribution of the Governance Levers Matrix is its capacity to explicitly address the complex interactions between drivers and the consequent trade-offs and synergies between ecosystem services and biodiversity outcomes. Moving beyond a simple one-lever, one-outcome model, this analytical dimension is critical for anticipating unintended consequences, navigating management dilemmas, and identifying potential win-win scenarios for multifunctional landscapes.

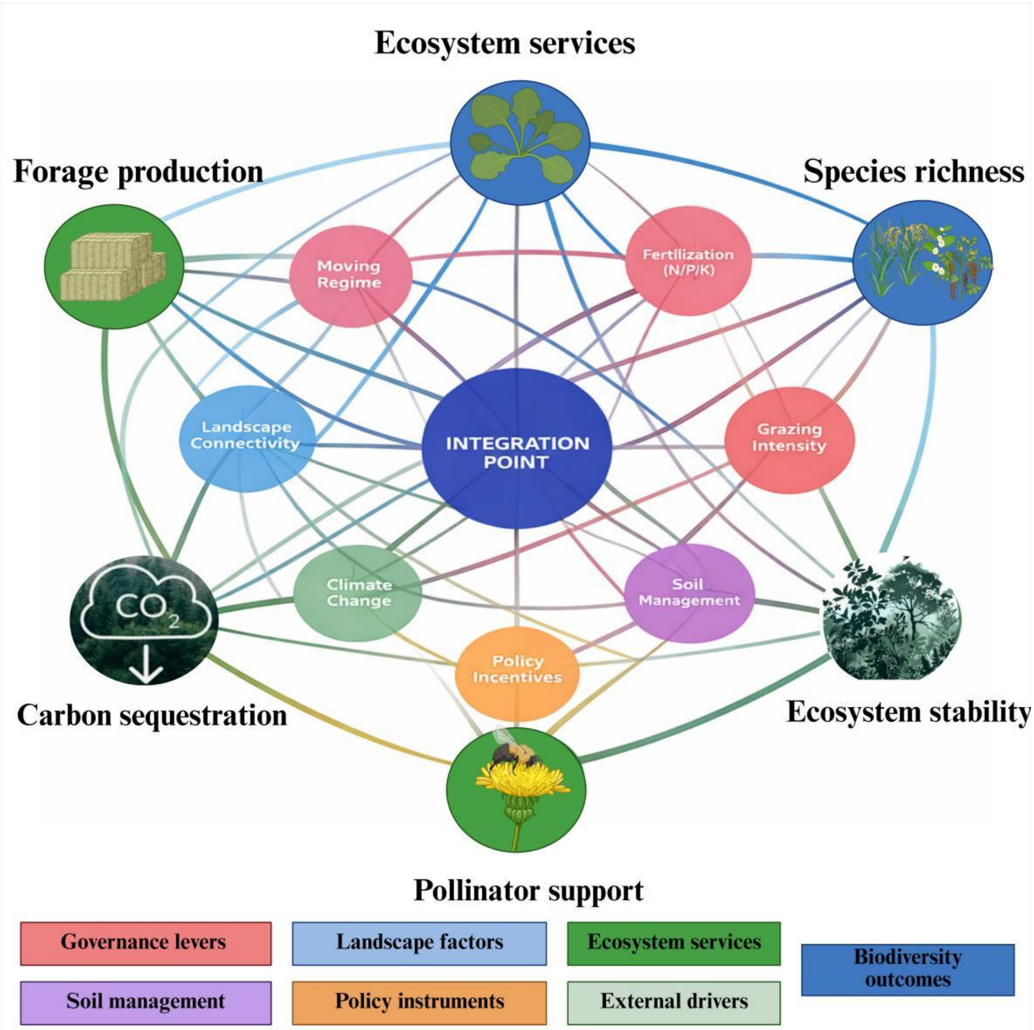

Figure 2. Multi-scale driver interactions in the Governance Levers Matrix. The network diagram shows relationships between field-scale governance levers (center), landscape factors (middle ring), and biodiversity/ecosystem service outcomes (outer ring). Line thickness indicates interaction strength.

4.1 Key Trade-offs

4.1.1 Forage Production vs. Species Richness: One of the most pervasive and well-documented trade-offs in managed grassland systems is between forage production and plant species richness. Agricultural intensification, driven primarily by nitrogen fertilization, reliably increases biomass productivity but at the cost of biotic simplification, as it favors fast-growing, competitive grass species and excludes less competitive forbs (Enescu et al. 2025, Linabury 2025). This creates a central tension for sustainable management, where land managers face economic imperatives to maximize short-term yield while conservation policies advocate for maintaining high levels of biodiversity.

4.1.2 Short-term vs. Long-term Outcomes: A related and equally critical trade-off exists between short-term productivity gains and long-term ecosystem stability and resilience. For instance, high stocking rates may maintain a short, open sward that benefits certain plant species initially but can lead to soil compaction, reduced infiltration, and degradation of the soil resource base over time. The matrix framework explicitly incorporates these temporal dynamics, emphasizing that effective governance requires evaluating management actions not just by their immediate effects but by their legacy impacts on ecological resilience and future service provision.

4.2 Key Synergies

4.2.1 Carbon Sequestration and Biodiversity: In contrast to the production-diversity trade-off, carbon sequestration and biodiversity conservation often exhibit positive synergies in grassland systems. Diverse plant communities enhance soil carbon storage through mechanisms such as greater and more varied root biomass production, which increases carbon inputs, and through complementary resource use that fosters more efficient nutrient cycling (Tariq et al. 2024). This synergy provides a compelling foundation for integrated management strategies that simultaneously advance climate change mitigation and biodiversity conservation goals.

4.2.2 Pollination and Forage Quality: Another significant synergy exists between pollination services and forage quality. Flower-rich grasslands sustain diverse pollinator communities, which provide essential pollination services both within the grassland and for adjacent crops. Crucially, legume species—key contributors to forage nutritional quality through biological nitrogen fixation—are highly dependent on insect pollination. Therefore, management practices that maintain flowering plant diversity, such as reduced mowing frequency or spatial zoning, can create a positive feedback loop, enhancing both pollination ecosystem services and forage quality (Parmentier et al. 2024).

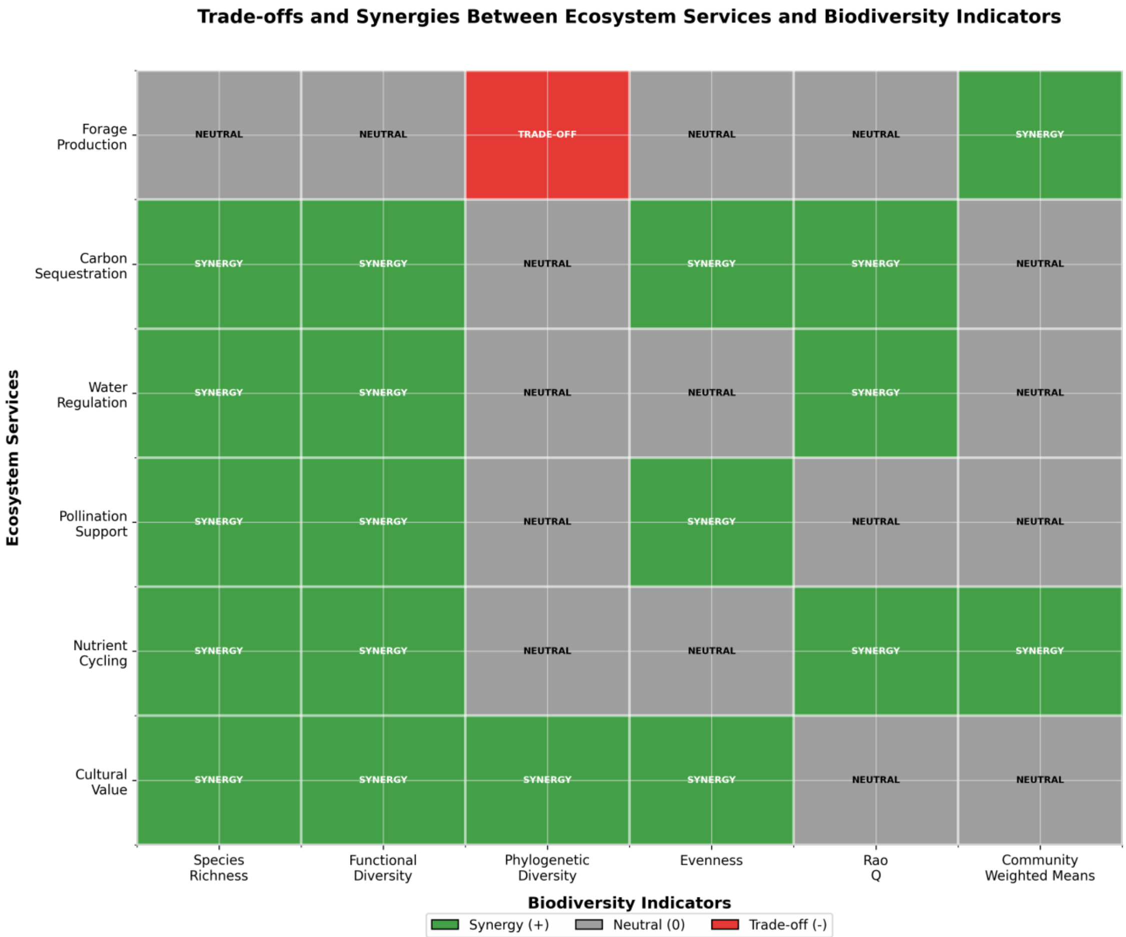

Figure 3. Trade-offs and synergies matrix showing relationships between ecosystem services (rows) and biodiversity indicators (columns). Green cells indicate synergies, red cells indicate trade-offs, and gray cells indicate neutral relationships.

5. Case Studies and Applications

The Governance Levers Matrix is designed as an applied framework to guide decision-making across diverse grassland systems and management contexts. The following case studies illustrate its practical utility in diagnosing challenges and informing more effective interventions.

5.1 European Agri-Environment Schemes

European agri-environment schemes (AES) represent one of the world's most extensive policy investments in grassland conservation. Despite substantial financial commitment, their ecological effectiveness has been inconsistent and often disappointing (Hecker et al. 2024). Applying the Governance Levers Matrix to this context reveals structural weaknesses and pathways for improvement.

First, the analysis shows that many AES prescriptions focus narrowly on field-scale management practices (e.g., specific mowing dates, fertilizer restrictions) while largely ignoring landscape-scale constraints. The matrix framework suggests that effectiveness could be significantly enhanced by incorporating multi-scale requirements, such as ensuring minimum habitat connectivity or incentivizing coordinated implementation across clusters of farms to create functional ecological networks. Second, the framework highlights a misalignment between means-based and outcome-based incentives. Traditional AES typically pay for the implementation of prescribed practices (a means), whereas the matrix emphasizes achieving desired biodiversity and service outcomes. Consequently, emerging pilot programs in Europe that adopt outcome-based payments rewarding farmers for measurable increases in indicator species or vegetation quality represent a promising innovation that aligns more closely with the matrix's logic (Saba 2025).

5.2 North American Rangeland Management

The vast rangelands of North America present a different set of challenges, often involving extensive grazing on public or privately owned lands. Here, the matrix framework underscores the critical importance of adaptive grazing management that is responsive to both seasonal variability and long-term vegetation trajectories. Systems such as rotational or multi-paddock grazing, which strategically vary stocking density, timing, and duration of grazing across multiple pastures, can when informed by monitoring of key biodiversity indicators help balance livestock production objectives with the maintenance of plant community diversity and soil health (Milazzo et al. 2023). The framework clarifies that the "lever" is not the grazing system itself, but the adaptive decision rules that govern its implementation based on ecological feedback.

5.3 Asian Grassland Restoration

Large-scale grassland restoration efforts in Asia, particularly the monumental programs in China and Mongolia, exemplify the challenges of rehabilitating degraded ecosystems. China's multi-billion-dollar initiatives have implemented sweeping measures including grazing bans, rotational grazing, and reseeding. The Governance Levers Matrix provides a diagnostic lens for these efforts, suggesting that long-term success depends on addressing drivers across all three scales simultaneously. This means coupling field-scale interventions (reseedings) with landscape-scale planning to ensure habitat connectivity for species recovery, while also deploying policy-scale levers such as alternative livelihood programs that address the socio-economic root causes of overexploitation (Palley 2025). The matrix thus advocates for an integrated approach that recognizes ecological recovery as a socio-ecological process.

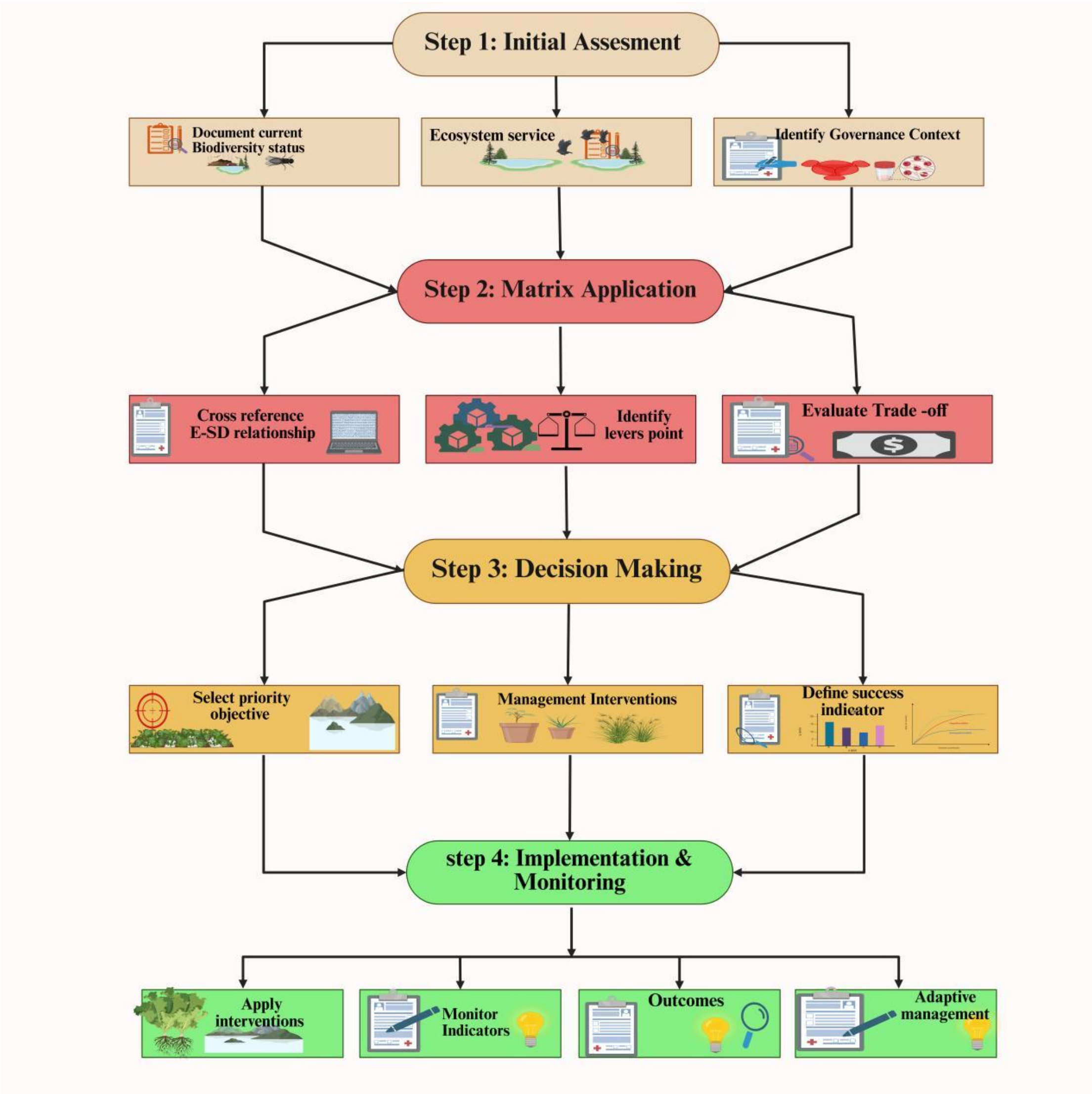

Figure 4. Application flowchart for the Governance Levers Matrix. The framework guides users through a four-step process: initial assessment, matrix application, decision-making, and implementation with adaptive feedback loops.

6 Future Research Directions

While the Governance Levers Matrix establishes a comprehensive framework for integrating ecosystem services, biodiversity indicators, and governance mechanisms, its development also highlights critical knowledge gaps and methodological frontiers. Addressing these will be essential for transforming the framework from a conceptual heuristic into a robust, predictive, and widely applicable tool for governance.

6.1 Quantifying Matrix Relationships

A primary limitation of the current synthesis is that many relationships within the matrix are described qualitatively. A major research priority is the quantitative characterization of these linkages to enable more precise management targeting. This includes: (1) developing empirical response functions that describe how specific ecosystem services change along continuous gradients of biodiversity indicators (e.g., soil carbon as a function of functional diversity); (2) conducting threshold analyses to identify non-linear tipping points or critical breakpoints where small adjustments in a governance lever produce disproportionate changes in outcomes (Li et al. 2024); and (3) quantifying interaction effects to understand how multiple levers (e.g., grazing and mowing) combine whether additively, synergistically, or antagonistically to influence biodiversity and services.

6.2 Integrating Social-Ecological Feedbacks

The current iteration of the matrix primarily treats governance levers as external inputs driving ecological outcomes. Future research must explicitly integrate dynamic social-ecological feedbacks, recognizing that the delivery of ecosystem services alters human well-being, perceptions, and economic behavior, which in turn reshape governance decisions and management practices (Li et al. 2024). Methodologically, agent-based modeling offers a powerful approach to simulate these complex feedbacks, exploring how heterogeneous landowner decisions, influenced by policy incentives and perceived ecological changes, collectively shape landscape-scale outcomes over time (Fertő et al. 2025).

6.3 Developing Digital Tools

To realize its full potential as a decision-support system, the matrix framework must be operationalized through accessible digital tools. Priority developments include: (1) interactive decision-support software that guides practitioners through applying the matrix to their specific context, visualizing trade-offs and suggesting lever combinations; (2) integration with remote sensing platforms that provide near-real-time data on biodiversity indicators (e.g., spectral diversity) at landscape scales, enabling adaptive monitoring (Zhidebayeva et al. 2025); and (3) scenario modeling tools that allow users to project probable outcomes under different management or climate scenarios, moving from reactive to proactive planning.

6.4 Climate Change Adaptation

Climate change represents a pervasive and transformative force that will fundamentally alter the context for all grassland governance. Future research must urgently extend the matrix framework to explicitly address adaptation. Key tasks include: (1) identifying climate-resilience levers practices that enhance ecosystem capacity to absorb disturbance and reorganize (e.g., maintaining genetic diversity, fostering structural heterogeneity); (2) reassessing how climate change modifies existing trade-offs and synergies between services, potentially intensifying conflicts or creating new opportunities; and (3) developing iterative adaptive management protocols that are embedded within the matrix logic, enabling management to evolve in response to monitored climatic impacts and ecological changes (Kachergis et al. 2022).

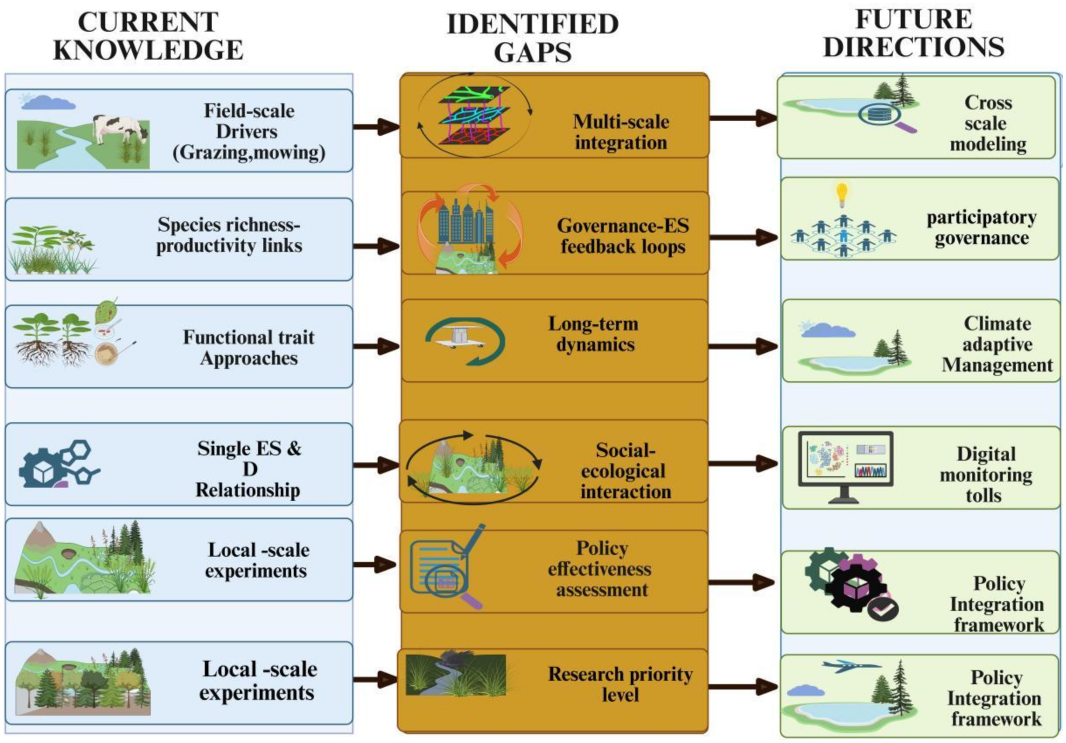

Figure 5. Research gaps and future directions map. The diagram shows the progression from current knowledge (left column) through identified gaps (center) to

future research priorities (right column), with priority levels indicated by color coding.

7 Conclusion and Policy Recommendations

The Governance Levers Matrix developed in this review provides a robust, integrative framework designed to bridge the persistent gap between ecological science and actionable policy for grassland systems. By systematically linking ecosystem services as desired outcomes, biodiversity indicators as measurable states, and governance mechanisms as intervention points, the framework offers a structured pathway to translate complex research into effective conservation and sustainable land management strategies.

This synthesis yields several overarching insights that are critical for future stewardship. First, scale integration is non-negotiable. Effective governance must simultaneously address field-level management practices, landscape-scale ecological patterns, and policy-scale institutional arrangements, as interventions at any single scale are often constrained or enabled by conditions at other levels. Second, trade-offs are inherent but can be navigated. The matrix makes the inevitable conflicts between objectives such as forage production versus species richness explicit, allowing for more transparent and informed decision-making. While some trade-offs can be mitigated through innovative management design, others require clear societal prioritization. Third, collective action is a prerequisite for success. Many of the most impactful governance levers, particularly those operating at the landscape scale, transcend individual property boundaries, necessitating coordination mechanisms that engage multiple stakeholders towards common ecological goals.

To translate these insights into tangible progress, we derive the following concrete policy recommendations from the matrix framework:

1. **Reform Agri-Environment Schemes (AES):** Policies should transition from prescribing specific management practices to rewarding verifiable ecological outcomes. Implementing outcome-based payment systems that compensate farmers for achieving measurable biodiversity and ecosystem service targets would align economic incentives directly with conservation goals. Furthermore, AES must

incorporate landscape-scale requirements, such as habitat connectivity thresholds, to incentivize collective action across farms rather than isolated parcels.

2. Support Landscape-Scale Coordination: Effective governance requires institutional innovation to facilitate coordination beyond the farm gate. Policymakers should establish and fund collaborative governance bodies, such as farmer collectives or watershed partnerships, empowered to plan and implement conservation actions at ecologically meaningful scales. This approach is essential for managing levers like habitat connectivity and regional species pools.

3. Invest in Integrated Monitoring and Adaptive Management: A cornerstone of evidence-based governance is robust, long-term monitoring. Investment is urgently needed to develop integrated monitoring systems that track key biodiversity indicators and ecosystem service flows simultaneously. This data must then feed into formal adaptive management cycles, allowing policies and practices to be iteratively refined in response to observed ecological feedback and changing environmental conditions.

4. Mainstream Climate Adaptation: Climate resilience must be embedded as a core objective within all grassland governance frameworks. This requires identifying and promoting specific management levers that enhance adaptive capacity (e.g., maintaining genetic diversity, increasing structural heterogeneity) and systematically evaluating how climate change will alter existing service trade-offs and synergies.

5. Foster Inclusive, Participatory Governance: The legitimacy and effectiveness of conservation initiatives are vastly improved through inclusive processes. Policymakers must create genuine avenues for meaningful stakeholder engagement, involving farmers, landowners, Indigenous communities, conservation organizations, and local governments in the co-design, implementation, and evaluation of grassland programs. Participatory approaches ensure that management strategies are socially equitable, locally relevant, and more likely to be sustained over the long term.

In conclusion, the Governance Levers Matrix moves the discourse from understanding grassland complexity toward strategically managing it. By providing a coherent architecture to organize knowledge and identify intervention points, the framework equips scientists, policymakers, and land managers with a powerful tool to navigate the socio-ecological challenges of the 21st century and steer grassland ecosystems toward a more resilient and multifunctional future.

Authors' Contributions:

Aleena*: Conceptualization, literature search and screening, data extraction, synthesis, original draft writing,visualization and correspondence.

Maryam Saleem: Helps in statistics, Literature review, data curation, reference organization, and manuscript editing.

Dr. Ghazala Yasmeen: Literature acquisition, critical review, and framework verification.

Mushtaq Ahmad*: Conceptualization, supervision, critical revision, and correspondence.

All authors read and approved the final manuscript.

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