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Review

Biodiversity loss in steppe ecosystems: a comprehensive review of conservation strategies

Zhuldyz Zhanassova [1*]

[1] University of International Business, Department of Tourism and Hospitality, Almaty, Kazakhstan; (Z.Z.) zhuldyzzhanassova@gmail.com, https://orcid.org/0009-0007-4683-1853

* **Corresponding author:** *Zhuldyz Zhanassova, Kazakhstan, Almaty 050031, 522/1 Raiymbek avenue, zhuldyzzhanassova@gmail.com, +77072557586*

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Abstract: Steppe and grassland ecosystems are among the most biologically diverse yet increasingly threatened terrestrial biomes, supporting unique biodiversity and providing essential ecosystem services. However, these ecosystems are experiencing rapid biodiversity loss due to agricultural expansion, overgrazing, habitat fragmentation, land-use change, invasive species, and climate change. Understanding recent advances in conservation research is therefore essential for developing effective management strategies and evidence-based environmental policies. This study presents a systematic bibliometric review of empirical research on biodiversity loss and conservation strategies in steppe ecosystems published between 2020 and 2025. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, 65 peer-reviewed articles were identified from the Scopus database through a structured Boolean search and a multi-stage screening process. The selected studies represent research conducted in 25 countries, with the highest publication output from the United States (n = 11), Germany (n = 6), and China (n = 6). Field surveys and field-based ecological studies were the dominant research methods (n = 39), followed by remote sensing and GIS approaches (n = 13), long-term ecological monitoring (n = 4), and species distribution modelling (n = 3). The review identified five major research themes: grazing impacts on plant diversity, habitat fragmentation, protected area effectiveness, ecological restoration, and climate-driven shifts in species distributions. The findings reveal considerable geographical gaps in conservation research, particularly in Central Asia and Kazakhstan, despite the extensive distribution and ecological significance of their steppe ecosystems. This review synthesises current empirical evidence, identifies methodological trends and research gaps, and provides recommendations for future interdisciplinary studies and policy development to strengthen biodiversity conservation and promote the long-term sustainable management of steppe ecosystems.

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1 Introduction

Steppe and temperate grassland ecosystems cover approximately 40 percent of Earth's terrestrial surface and support extraordinary biological diversity across all trophic levels. These biomes provide critical ecosystem services including carbon sequestration, water regulation, and the livelihoods of pastoralist communities on every inhabited continent. Despite their global significance, temperate grasslands have experienced disproportionate rates of conversion, fragmentation, and degradation, with native grassland losses in some regions exceeding 80 to 95 percent of historical extents (Fogarty et al., 2020). Agricultural expansion, urban development, overgrazing, fire suppression, and climate change have collectively driven declines in plant, invertebrate, and vertebrate diversity across steppe systems worldwide (Ambrósio et al., 2024; Luo et al., 2025).

The escalating pace of biodiversity loss has galvanised international conservation commitments. The Kunming-Montreal Global Biodiversity Framework adopted in December 2022 set the 30x30 target of protecting 30 percent of terrestrial and marine areas by 2030, with specific attention to ecosystems under severe threat. However, policy implementation remains uneven, and steppe biomes frequently receive less attention than forest systems in national biodiversity strategies. A growing body of empirical research is now addressing these gaps, spanning topics from livestock grazing management (Dong et al., 2025) to protected area effectiveness (Gameiro et al., 2020), restoration ecology (Watkinson et al., 2025), and climate-driven range shifts (Gao et al., 2025).

Despite this growing research activity, no comprehensive synthesis of post-2020 empirical literature on steppe biodiversity exists. The present systematic review addresses this gap by synthesising 65 empirical studies identified through a structured PRISMA-compliant search of the Scopus database. The objectives are: (1) to map the geographic and temporal distribution of steppe biodiversity research; (2) to identify and synthesise evidence on the principal drivers of biodiversity loss; (3) to evaluate conservation and restoration strategies examined in empirical studies; and (4) to identify critical research gaps and priorities for future investigation.

2 Materials and methods

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines adapted for bibliometric studies. The Scopus database was selected as the primary source owing to its comprehensive coverage of peer-reviewed scientific literature in the environmental and ecological sciences. A Boolean search was conducted using the following query: TITLE-ABS-KEY (("biodiversity loss" OR "biodiversity decline" OR "species loss" OR "habitat loss") AND ("steppe*" OR "grassland*" OR "dryland*" OR "semi-arid*") AND ("conservation strateg*" OR "conservation plan*" OR "protected area*" OR "ecosystem management" OR "restoration strateg*")). The search was conducted in June 2025 and returned an initial set of 397 records.

Records were screened in sequential stages, as illustrated in Figure 1. A publication year filter was applied first, restricting results to 2020 to 2025 and reducing the pool to 185 records. The document type filter, limiting results to original research articles, reduced this further to 166 records. Removal of duplicate entries yielded 161 records, and application of the open access filter produced 108 records. Title and abstract screening for relevance to steppe or grassland ecosystems reduced the pool to 82 records. Finally, full-text assessment of each article for empirical content excluded a further 17 records that were found to be systematic reviews, meta-analyses, or purely theoretical studies, resulting in a final corpus of 65 articles included in the analysis.

Articles were included if they: (1) reported original empirical data collected through field surveys, field experiments, remote sensing analyses, or long-term monitoring programmes; (2) focused on steppe, temperate grassland, semi-arid, or dryland ecosystems; (3) addressed biodiversity metrics such as species richness, abundance, community composition, or habitat quality; and (4) were published in English in Scopus-indexed, peer-reviewed journals between January 2020 and December 2025. Articles were excluded if they were systematic reviews or meta-analyses without new empirical data, purely theoretical or modelling studies without field validation, or studies focused solely on non-steppe ecosystems such as forests or aquatic habitats.

For each included article, the following variables were extracted: authors and year of publication, article title, journal name, country of study identified from author affiliations, methodological approach, and key thematic content based on author keywords and abstracts. Methodological approaches were categorised into six types: field survey, field experiment, remote sensing and GIS analysis, long-term monitoring, species distribution modelling, and statistical analysis. Thematic coding was performed inductively based on author keywords and abstract content, and articles were assigned to one primary thematic cluster.

Descriptive statistics and frequency analyses were performed to characterise the distribution of studies across geographic, temporal, and methodological dimensions.

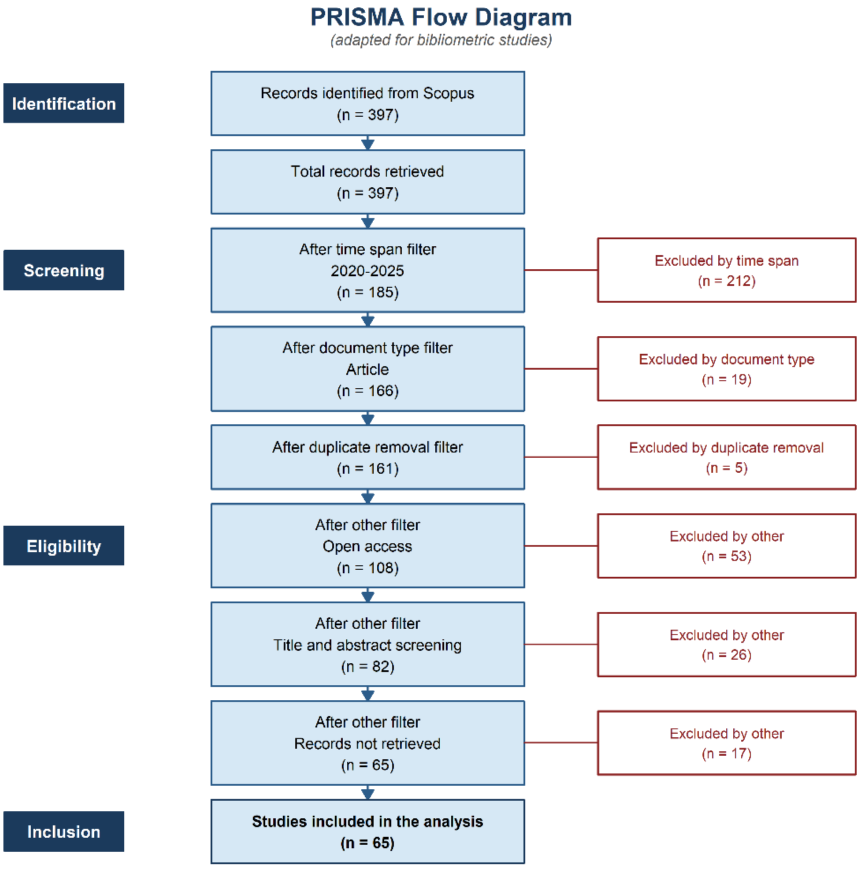

Figure 1. PRISMA 2020 flow diagram illustrating the article selection process from initial Scopus search (n = 397) to final included studies (n = 65).

3 Results

3.1 Overview and temporal trends

The 65 included studies (Table 1) were published across the period 2020 to 2025, with a pronounced upward trend: 3 articles in 2020, 6 in 2021, 10 in 2022, 9 in 2023, 11 in 2024, and 26 in 2025. This acceleration likely reflects growing policy urgency following the adoption of the Kunming-Montreal Global Biodiversity Framework. Studies were published across 40 journals, most frequently in Biological Conservation (n = 5), Ecological Indicators (n = 4), and Landscape Ecology (n = 4).

Table 1. Distribution of 65 included studies by journal (n = number of articles; % = percentage of total).

No.	Journal	n	%
1	Biological Conservation	5	7.7
2	Ecological Indicators	4	6.2
3	Landscape Ecology	4	6.2
4	Diversity	3	4.6
5	Global Ecology and Conservation	3	4.6
6	Restoration Ecology	3	4.6
7	Ecological Processes	2	3.1
8	Ecosphere	2	3.1
9	Ecology and Evolution	2	3.1
10	American Journal of Primatology	1	1.5

Table 1. (Continued)

No.	Journal	n	%
11	Animals	1	1.5
12	Applied Vegetation Science	1	1.5
13	Austral Ecology	1	1.5
14	Biology	1	1.5
15	Birds	1	1.5
16	Biosystems Diversity	1	1.5
17	Catena	1	1.5
18	Desenvolvimento e Meio Ambiente	1	1.5
19	Diversity and Distributions	1	1.5
20	Ecological Applications	1	1.5
21	Ecology	1	1.5
22	Endangered Species Research	1	1.5
23	Environmental Monitoring and Assessment	1	1.5
24	Environmental Problems	1	1.5
25	Environmental Research Letters	1	1.5
26	Forest Ecology and Management	1	1.5
27	Genome Biology	1	1.5
28	Global Change Biology	1	1.5
29	Insect Conservation and Diversity	1	1.5
30	Journal of Animal Ecology	1	1.5
31	Journal of Applied Ecology	1	1.5
32	Journal of Ecology	1	1.5
33	Journal of Environmental Management	1	1.5
34	Journal of Insect Conservation	1	1.5
35	Land	1	1.5
36	Land Degradation and Development	1	1.5
37	Land Use Policy	1	1.5
38	Ornis Hungarica	1	1.5
39	ORYX	1	1.5
40	Perspectives in Ecology and Conservation	1	1.5
41	Remote Sensing	1	1.5
42	Revista de Biología Tropical	1	1.5
43	Scientific Reports	1	1.5
44	Sustainability	1	1.5
45	Wildlife Society Bulletin	1	1.5
Total		**65**	**100.0**

3.2 Geographic distribution

The included studies originated from 25 countries, as shown in Figure 2, with the highest output from the United States (n = 11), Germany (n = 6), and China (n = 6), followed by Brazil (n = 4), and the United Kingdom, Canada, Argentina, South Africa, and Italy (n = 3 each). Studies from Austria (Schwaiger, 2022; Probst, 2025), France (Ghasemi et al., 2025; Chenot-Lescure et al., 2022), Spain (Parengal et al., 2025; Muñoz-Reinoso, 2023), Switzerland (Achury et al., 2025; Perrin et al., 2025), Ukraine (Dubyna et al., 2023; Uvaieva et al., 2025), India (Dutta & Jhala, 2021; Jhala et al., 2021), and Australia (Stoudmann et al., 2024; Lee et al., 2023) each contributed two articles. Single studies originated from the Netherlands (Ambrósio et al., 2024), New Zealand (Pedley et al., 2023), Czech Republic (Segrestin et al., 2025), Slovenia (Gazoulis et al., 2022), Tanzania (Rija, 2022), South Korea (Abedin et al., 2024), Thailand (Jahan et al., 2022), Portugal (Crispim-Mendes et al., 2024), and Sweden (Narváez-Torres et al., 2025).

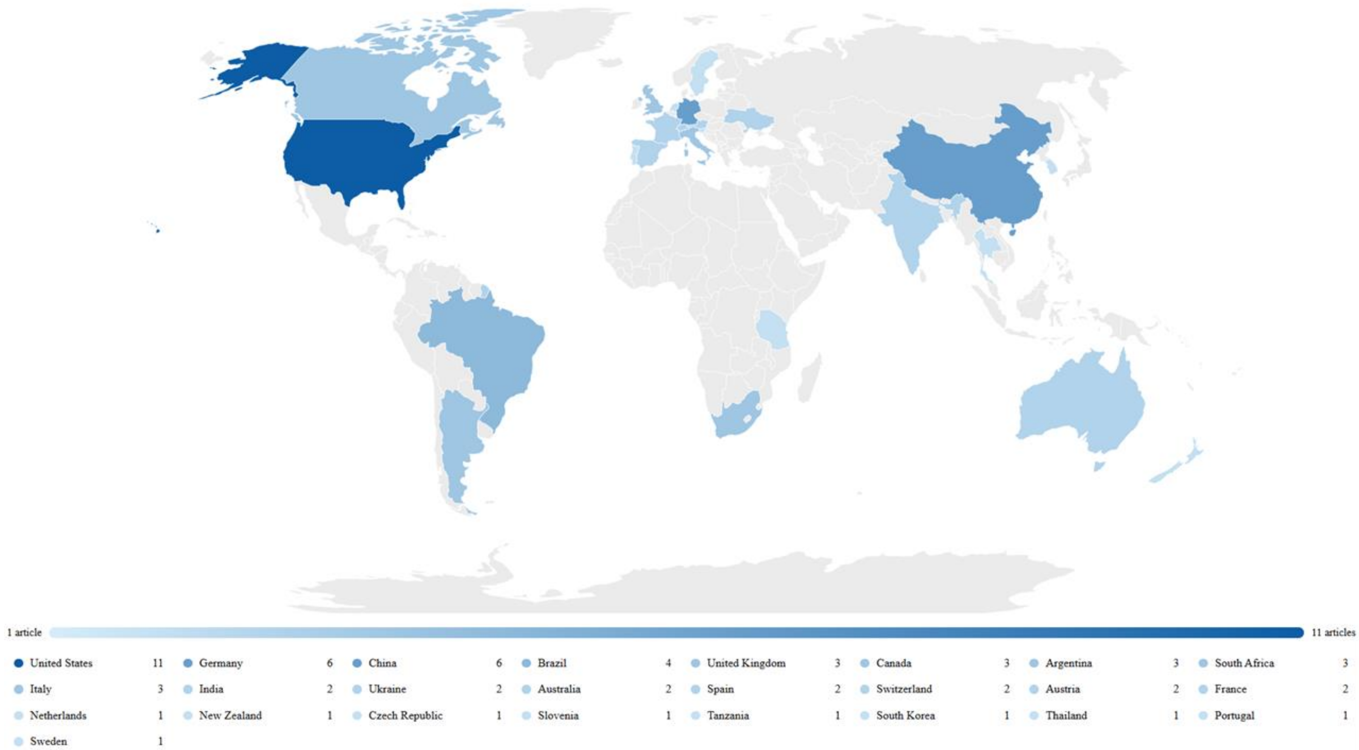

Figure 2. Geographic distribution of the 65 included empirical studies across 25 countries. Colour intensity (light to dark blue) corresponds to number of publications per country (range: 1 to 11 articles).

A critical geographic gap was identified in Central Asia. No empirical open-access studies from Kazakhstan, Uzbekistan, Mongolia, or other Central Asian countries met the inclusion criteria, despite these regions containing the largest remaining contiguous steppe areas on Earth. This underrepresentation has significant implications for global conservation planning, as evidence-based management frameworks cannot be developed without locally-grounded empirical data.

3.3 Keyword co-occurrence analysis

Figure 3 presents the keyword co-occurrence network generated using VOSviewer based on the author keywords of the 65 included studies. Six thematic clusters were identified, reflecting the dominant research foci in the literature: (1) nature conservation and policy (red cluster); (2) climate change and environmental factors (orange/yellow cluster); (3) conservation planning and species distribution (green cluster); (4) ecological restoration and landscape connectivity (blue cluster); (5) pasture and agroecosystem management (purple cluster); and (6) grassland ecosystem and dryland dynamics (pink cluster). The most frequently co-occurring keywords were nature, conservation planning, environmental factor, and ecological restoration, indicating that these concepts form the conceptual core of current steppe biodiversity research.

3.4 Methodological profile

Field surveys and observational field studies were the dominant methodological approach (n = 39). Remote sensing and GIS analyses were employed in 13 studies, including vegetation change monitoring (Lu et al., 2022), land cover mapping (Rodrigues et al., 2025; Pavlacky et al., 2022), and habitat suitability assessment (Fowler et al., 2024; Paterson et al., 2024). Long-term monitoring programmes were the basis of four studies (Bernath-Plaisted et al., 2025; Ogan et al., 2022; Richiardi et al., 2025; Deutsch et al., 2024). Species distribution modelling was used in three studies (Jhala et al., 2021; Crispim-Mendes et al., 2024; Luo et al., 2025). Field experiments examining the effects of specific management interventions were conducted in four studies (Segrestin et al., 2025; Watkinson et al., 2025; Nascimento et al., 2025; Chenot-Lescure et al., 2022).

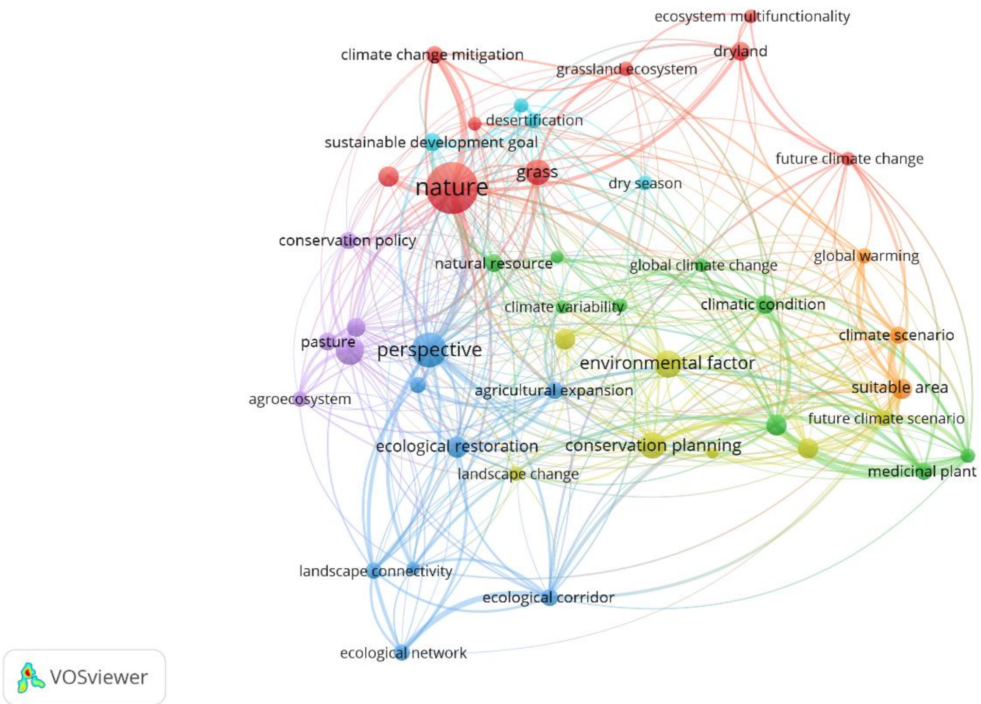

Figure 3. Keyword co-occurrence network of included studies generated using VOSviewer (n = 65).

3.5 Theme 1: Grazing impacts on steppe biodiversity

Grazing by domestic livestock is the most pervasive anthropogenic influence on steppe ecosystems. Dong et al. (2025) demonstrated that expansion of native poisonous plants in degraded Tibetan pastures was mediated by soil processes altered by overgrazing, paradoxically increasing plant diversity in degraded sites through facilitation mechanisms. Igl et al. (2023) found that conversion of Conservation Reserve Program grasslands to cropland in the northern Great Plains resulted in significant loss of grassland-dependent bird species, with the removal of grassland cover eliminating habitat for both obligate and facultative grassland species. These contrasting findings highlight the complexity of grazing effects and the importance of spatially and taxonomically explicit empirical approaches.

3.6 Theme 2: Habitat loss and land use change

Fogarty et al. (2020) documented progressive encroachment of woody vegetation into native Nebraska grasslands associated with fire suppression and altered grazing regimes. Fernandes et al. (2025) assessed extinction risk in South American pampas grasslands, finding that endemic Cactaceae were disproportionately threatened by habitat conversion. Pedley et al. (2023) examined natural regeneration of woody vegetation into New Zealand grasslands, reporting significant reductions in open-habitat specialist species. Niemuth et al. (2021) showed that grassland bird conservation in the United States was strongly linked to maintenance of large unfragmented grassland patches, with Conservation Reserve Program enrolment directly predicting population recovery. Stoudmann et al. (2024) evaluated conservation outcomes in Australian agricultural landscapes, demonstrating that targeted on-farm conservation agreements significantly improved vegetation structural complexity.

Lakner et al. (2020) found that combining management plans with payment for ecosystem services schemes in German calcareous grasslands achieved higher plant species richness targets than either instrument alone. Perrin et al. (2025) examined habitat fragmentation effects on insect diversity in Swiss grasslands, showing that fragment size and connectivity were the strongest predictors of species richness. Ivey et al. (2025) documented ongoing decline in landcover suitability for sandhill crane habitat in United States grasslands driven by agricultural conversion. Deutsch et al. (2024) used long-term monitoring in Argentine Patagonian steppes to show substantial reductions in small mammal diversity linked to grazing intensity and land tenure changes. Probst and Probst (2025) investigated winter ecology of the hen harrier in Austrian steppe systems, finding that landscape-level grassland cover predicted foraging success and survival. Begosh et al. (2022) demonstrated that semi-natural grassland edges maintained significantly higher floral diversity than cropland-dominated landscapes in United States dryland systems.

Ding et al. (2022) assessed probable extirpation of the hog deer from Chinese steppe regions, attributing local extinction to habitat loss through conversion of floodplain grasslands to rice cultivation. Ramírez and Säumel (2023) used betadiversity analysis to demonstrate that land use change in South American grasslands drove replacement of grassland specialist communities by generalist species. Pavlacky et al. (2022) applied remote sensing and field data to evaluate the effectiveness of United States grassland conservation programmes for migratory shorebirds.

3.7 Theme 3: Protected area effectiveness

Gameiro et al. (2020) found mixed effectiveness of European Natura 2000 special protection areas for steppe birds in Portugal, with some species recovering within protected zones while others continued declining due to inadequate internal management. Abedin et al. (2024) modelled the distribution of a globally threatened steppe bird in South Korea and identified critical gaps in the protected area network relative to the species' habitat requirements. Frenzel et al. (2025) demonstrated that higher bee species richness in German grassland-cropland mosaics was associated with the proximity and area of semi-natural habitats within 500 m, supporting landscape-scale conservation. Schwaiger et al. (2022) documented pronounced species turnover without net species loss in Austrian grasslands over 30 years, attributing change to management intensification within and outside protected areas.

Barros et al. (2023) evaluated community structure and conservation value of steppe bird assemblages in Ecuadorian grasslands, finding that traditionally managed grasslands supported higher diversity than intensively managed sites. Rodrigues et al. (2025) applied machine learning to Cerrado grassland land cover mapping in Brazil, improving precision of habitat change detection for conservation planning. Ghasemi et al. (2025) modelled ecosystem services in French Mediterranean grasslands, finding significant co-benefits for biodiversity and carbon storage from agricultural extensification policies. Richiardi et al. (2025) used remote sensing combined with long-term monitoring in Italian Natura 2000 grasslands to document progressive shrub encroachment despite protected status. Uvaieva et al. (2025) assessed the impact of military operations on natural vegetation in Ukrainian steppe using remote sensing, documenting widespread destruction of steppe plant communities. Hawkes et al. (2025) found that coordinated agri-environment scheme management at landscape scales significantly improved farmland bird outcomes in United Kingdom grasslands. Nunes et al. (2021) identified spatial mismatches between conservation area networks and grassland-dependent bird species ranges in the United States, highlighting the need for dynamic protected area planning. Smit et al. (2024) demonstrated that South African protected area boundaries were largely effective in preventing conversion but less effective in controlling internal shrub encroachment.

3.8 Theme 4: Ecological restoration

Dutta and Jhala (2021) investigated habitat requirements of the critically endangered great Indian bustard, providing detailed data essential for restoration site selection. Watkinson et al. (2025) demonstrated that greater sage-grouse habitat restoration through targeted native grass seeding in Canadian steppe significantly improved vegetation structural complexity within two growing seasons. Nascimento et al. (2025) evaluated the effectiveness of targeted habitat restoration for a threatened grassland raptor in South America, showing that vegetation structure restoration was the most important intervention. Narváez-Torres et al. (2025) assessed grassland restoration outcomes across Madagascar and other island steppe systems, identifying vegetation connectivity as the key metric for restoration success. Paterson et al. (2024) applied species distribution modelling combined with remote sensing to predict effects of targeted grassland restoration on a threatened shorebird in Canadian prairies. Luo et al. (2025) demonstrated that combined climate and land use change effects on North American grassland plant communities exceeded the impacts of either driver alone, with strong implications for climate-adaptive restoration design. Chenot-Lescure et al. (2022) compared multiple artificial seed sources for grassland restoration in Mediterranean France, identifying locally sourced seed mixes as most effective and cautioning against use of commercial non-local provenance mixtures.

3.9 Theme 5: Climate change responses

Ambrósio et al. (2024) modelled global sustainability scenarios and found that steppe and dryland systems were among the most sensitive to climate-driven habitat change. Parengal et al. (2025) documented distribution shifts and habitat contractions in an endangered grassland bird in India linked to temperature and precipitation trends over three decades. Gao et al. (2025) projected substantial climate-driven redistribution of steppe bird species in Inner Mongolia, with implications for the adequacy of existing protected area networks. Ogan et al. (2022) used long-term resurvey data from German grasslands to demonstrate pronounced species turnover linked to climate warming, with thermophilous species expanding at the expense of cold-adapted specialists.

3.10 Theme 6: Species distribution and community ecology

The largest thematic cluster (n = 26) comprised studies examining species distributions, community composition, and ecological interactions in steppe and grassland systems. Mills et al. (2023) quantified avian biodiversity responses to habitat heterogeneity across Brazilian grasslands. Han et al. (2025) examined niche overlap between two sympatric steppe raptor species in China, providing evidence for competitive exclusion as a driver of local distribution. Germain et al. (2025) investigated geomorphic impacts of fossorial mammals in Canadian steppe, revealing important roles of burrowing species in soil turnover and vegetation patchiness. Menezes et al. (2025) assessed distribution and conservation status of endemic Cactaceae in Brazilian pampa grasslands, identifying in situ conservation priorities. Bernath-Plaisted et al. (2025) applied long-term monitoring to assess population trends for migratory grassland birds across United States steppe regions, finding significant declines in species dependent on native grassland structure. Rosas et al. (2021) characterised plant community composition across Argentine steppe using field surveys combined with remote sensing. Pretorius et al. (2023) demonstrated that preservation of large tracts of natural grassland in South Africa promoted significantly higher mammal diversity and biomass compared to smaller fragments.

Dubyna et al. (2023) documented plant community changes in Ukrainian steppe associated with management abandonment, showing progressive decline in steppe specialists and expansion of ruderal generalists. Jhala et al. (2021) modelled feasibility of reintroducing grassland megaherbivores in Indian steppe, identifying suitable areas currently outside the protected area network. Medina et al. (2021) demonstrated that burrowing mammal communities in Argentine pampas were strong predictors of plant community composition. Achury et al. (2025) showed that semi-natural habitat area within landscapes was the strongest determinant of arthropod species richness in Swiss grasslands. Gazoulis et al. (2022) quantified displacement of native grassland species by invasive Ailanthus altissima in Slovenian steppe margins. Tang et al. (2025) showed that climatic seasonality shaped insect community composition across Chinese steppe, with precipitation variability driving annual arthropod turnover. Rija (2022) demonstrated that local habitat characteristics, particularly vegetation density and flowering plant diversity, were stronger predictors of butterfly richness than landscape context in Tanzanian grasslands.

Meißner et al. (2025) applied genomic approaches to elucidate population structure of a threatened large mammal in South African grasslands, providing data for translocation planning. Muñoz-Reinoso

(2023) tracked directional vegetation transitions in Spanish grassland systems, demonstrating replacement of steppe grass communities by scrub under reduced grazing pressure. Jahan et al. (2022) identified grass height and litter depth as the most critical microhabitat parameters for grassland bird nest site selection in Thai savanna-grassland mosaics. Lu et al. (2022) revealed significant vegetation degradation hotspots in Chinese semi-arid steppe using multi-temporal satellite imagery. Fowler et al. (2024) demonstrated that grassland patch size and connectivity were stronger predictors of bird occurrence than local vegetation characteristics in United States steppe systems. Crispim-Mendes et al. (2024) projected habitat requirements for a threatened steppe bird in Portugal under multiple land use and climate scenarios, identifying critical conservation areas outside the existing protected area network. Meschini et al. (2024) demonstrated strong associations between breeding site selection and extensive cereal farming practices for a declining migratory grassland bird in Italian steppe. Anderle et al. (2024) found that targeted agri-environment measures significantly outperformed general extensification payments for maintaining multi-species grassland bird assemblages in Alpine foothills of Italy.

Lee et al. (2023) identified fire management as the key conservation intervention for a threatened grassland ant in Hong Kong shrub-grassland mosaics, using remotely sensed habitat suitability modelling. He et al. (2025) developed a scalable framework for large-scale analysis of ecosystem integrity in Chinese steppe using multi-source remote sensing data. Schöpke et al. (2024) demonstrated that semi-natural grassland strips significantly enhanced local plant diversity even under intensive farming regimes in German agricultural landscapes.

4 Discussion

This systematic review synthesises empirical evidence from 65 studies and provides a comprehensive overview of the current state of knowledge on biodiversity loss and conservation in steppe ecosystems. Several cross-cutting findings emerge from this synthesis.

The accelerating trajectory of publication output, culminating in 26 articles in 2025 alone, reflects growing scientific and policy recognition of the conservation crisis facing temperate grasslands. The adoption of the Kunming-Montreal Global Biodiversity Framework in 2022 has catalysed substantial new research examining the adequacy of existing protected area networks and the most effective strategies for expanding conservation coverage in grassland biomes. This momentum is encouraging, yet the absolute volume of research on steppe ecosystems remains far below that dedicated to forest systems, highlighting a persistent imbalance in conservation attention.

The geographic concentration of research in North America and Western Europe (Figure 2) reflects longstanding structural inequalities in global research investment. This is particularly consequential given that Kazakhstan alone harbours approximately 100 million hectares of steppe, representing the largest remaining block of near-natural temperate grassland on Earth, yet no empirical open-access studies from the region met inclusion criteria in this review. Addressing this gap requires sustained international investment in research infrastructure, open-access publication support, and collaborative programmes linking Central Asian scientists with international research networks.

The dominance of observational field studies and remote sensing approaches reflects the practical constraints of steppe research across large, often remote landscapes. However, the relative scarcity of manipulative field experiments limits causal inference regarding conservation intervention effectiveness. The experimental studies identified here (Segrestin et al., 2025; Watkinson et al., 2025; Nascimento et al., 2025; Chenot-Lescure et al., 2022) demonstrate the feasibility and scientific value of randomised management experiments in steppe systems. Long-term monitoring programmes (Bernath-Plaisted et al., 2025; Ogan et al., 2022; Richiardi et al., 2025; Deutsch et al., 2024) provide essential temporal context but require sustained institutional commitment.

The finding that protected areas frequently fail to fully protect steppe biodiversity, documented across multiple continents (Gameiro et al., 2020; Schwaiger et al., 2022; Richiardi et al., 2025; Smit et al., 2024), points to the need for landscape-scale conservation approaches. Agri-environment schemes (Lakner et al., 2020; Anderle et al., 2024; Hawkes et al., 2025), payments for ecosystem services (Stoudmann et al., 2024; Ghasemi et al., 2025), and collaborative agreements with private landowners provide consistent empirical support for complementary conservation tools when accompanied by appropriate monitoring and adaptive management.

Climate change emerges as a cross-cutting threat interacting with land use pressures to produce compound effects on steppe biodiversity (Ambrósio et al., 2024; Parengal et al., 2025; Gao et al., 2025; Ogan et al., 2022). Climate-adaptive conservation strategies, including dynamic protected area planning and climate-informed restoration site selection (Paterson et al., 2024; Luo et al., 2025), are urgently needed to maintain the long-term viability of steppe conservation investments.

5 Conclusion

This systematic bibliometric review synthesises empirical evidence from 65 peer-reviewed studies published between 2020 and 2025 on biodiversity loss and conservation strategies in steppe and grassland ecosystems worldwide. The analysis reveals a rapidly accelerating research output, a geographic concentration in North America and Western Europe, and a persistent underrepresentation of Central Asian steppe systems despite their global ecological significance. Together, these findings point to both the progress and the limitations of the current international conservation research landscape.

The five thematic clusters identified — grazing impacts, habitat fragmentation, protected area effectiveness, ecological restoration, and climate change responses — reflect the principal drivers and management levers currently documented in empirical literature. The consistent finding that protected areas alone are insufficient to halt biodiversity decline, observed across multiple continents, underscores the need for landscape-scale approaches that integrate agri-environment schemes, payments for ecosystem services, and collaborative governance with private landowners. Experimental restoration studies demonstrate that targeted interventions, including native seed mixes and managed grazing regimes, can produce measurable ecological recovery within short timeframes.

A critical gap identified by this review is the near-total absence of open-access empirical research from Kazakhstan and Central Asia in internationally indexed databases, despite the region harbouring the largest contiguous block of near-natural temperate grassland on Earth. Addressing this gap requires sustained investment in research infrastructure, capacity building, and open-access publication support for scientists working in the region. Future research priorities include long-term experimental studies on restoration effectiveness, dynamic conservation planning under climate change scenarios, and the development of region-specific biodiversity monitoring frameworks aligned with the Kunming-Montreal Global Biodiversity Framework targets.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Zhuldyz Zhanassova	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

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Biography of author

Zhuldyz Zhanassova
Department of Tourism and Hospitality, University of International Business, Almaty, Kazakhstan
Ecosystem, nature protection, environment
zhuldyzzhanassova@gmail.com
https://orcid.org/0009-0007-4683-1853