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Realizing the value of grassland ecosystem services: global practice and its inspiration for the karst desertification control area

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The conflict between grassland ecosystem conservation and economic development is an important but challenging question. Realizing the value of ecosystem services (ES) is considered to be a solution for the dual sustainability of ecology and economy. However, there is a lack of systematic understanding of value realization of grassland ES, especially in the karst desertification (KDC) area, which is still at an exploratory stage. We obtained 527 studies from 48 countries in the past 20years through the Scopus database, and systematically reviewed the current understandings and practices by the content analysis method, and enlightened the inspiration for the grassland in the KDC area. Results showed that: (i) Over the past 20years, the literature number showed a fluctuating growth trend, and the study areas are mainly concentrated in economically developed countries with rich grassland resources; (ii) Pathways such as grassland management and payment for ecosystem services (PES) are widely used to improve grassland ES and human well-being, and most studies have shown positive effects; (iii) Their performance is significantly impacted by stakeholders, governments, as well as the attributes of ES, and a path of government-led, stakeholder participation and market-oriented operation should be explored; and (iv) There are still some knowledge gaps, such as, uneven distribution of study areas, few effective pathways for realizing the public grassland ES value, and deficient linkage mechanisms of "grassland ES-industry development-economic system feedback-ecosystem protection," and so on. Based on our findings, we not only make recommendations for the current dilemma of realizing the value of grassland ES, but also put forward the enlightenments to the grassland in the KDC area based on experiences and lessons learned from global practices. The results can provide theoretical guidance for the ecological protection and sustainable development of grasslands in fragile areas.

KEYWORDS

grassland, ecosystem services, value realization, content analysis, karst desertification control, sustainability

Introduction

Grasslands, as one of the most widespread terrestrial ecosystems globally, not only provide habitat for plant and animal diversity, they also contribute food and cultural services to humanity (White et al., 1995; Bengtsson et al., 2019). However, the fragile ecological environment (Gossner et al., 2016; Ganguli and O'Rourke, 2022), coupled with unreasonable economic activities and undulate climate change (Ma et al., 2017; Maestre et al., 2022), leads to the degradation of grassland ecosystem (Bardgett et al., 2021). As a result, the ecosystem function of grasslands is impaired (Breidenbach et al., 2022), and the goods and services they provide are unable to meet the increasing demand for food and a beautiful environment. In this regard, it is important to find an economically and ecologically sustainable solution to synergistically maintain and enhance the grassland ES and human well-being.

Grassland in the KDC area is a special ecosystem formed by using ecological engineering measures (e.g., returning farmland to grassland, grassland establishment, etc.) to control karst desertification (a concentrated manifestation of karst land degradation; Xiong et al., 2023). In contrast to the grassland in non-karst area (e.g., the tropical and subtropical savannas and temperate steppes, and arctic-alpine grasslands, etc.), grasslands in the KDC area is a special ecosystem constrained by the complex and unique hydrological and carbonate geological conditions couple with sharp conflicts between population and land (Xiong et al., 2002). On the one hand, karst geology, hydrology, climate and biological processes are coupled, and matter and energy are constantly moving in different directions, ways and intensities (LeGrand, 1973; Yuan, 1988), driving the formation of a special ecological environment (Figure 1). In this environment, the sensitivity of ecosystem variation is high, the environmental capacity is low, and the disaster tolerance threshold is low. Under the regulation of positive and negative feedback effects of vulnerable environmental variables, the positive succession rate of ecosystems is slow and easy to interrupt, while the reverse succession rate is fast and difficult to recover (Yang, 1990; Yuan, 2001; Ford and Williams, 2007). On the other hand, high population pressure and traditional industries (e.g., hillside plowing) are prevalent (Yuan, 1997; Yan and Cai, 2015; Xiao and Xiong, 2022), coupled with limited livelihoods and fluctuating climate change (Grime et al., 2000; Chen C. et al., 2021), this is prone to form a vicious cycle of degraded ecosystem function—loss of ecological assets—reduction of livestock support services capacity—lower food and income for farmers—poverty traps (Chen Q. et al., 2021; Zuo et al., 2022). Currently, the "United Nations Decade on Ecosystem Restoration (2021–2030; UNEA, 2019)" delivers a rallying call to cope with the protection and revival of ecosystems for the benefit of nature and human. Grassland in the KDC area is the main position in response to the call of the United Nations, there is an urgent need to re-establish a bond between people and nature in order to address the ecological and economic trade-offs.

In order to reconcile ecology and economy, and turn environmental protection from a burden into an opportunity for economic development, ecologists and economists put forward the conception of value realization of ES (Wang, 2016; Zhang et al., 2021). The concept considers the ecological environment as the core production factor, such as land, labor force and technology; internalizes the externality of ecological environmental protection benefits by integrating them into the whole process of social production, such as production, distribution, exchange and consumption; and establishes a long-term mechanism for transforming "lucid waters and lush mountains" to "invaluable assets" (Wang and Wang, 2020). That is, by realizing the value of natural

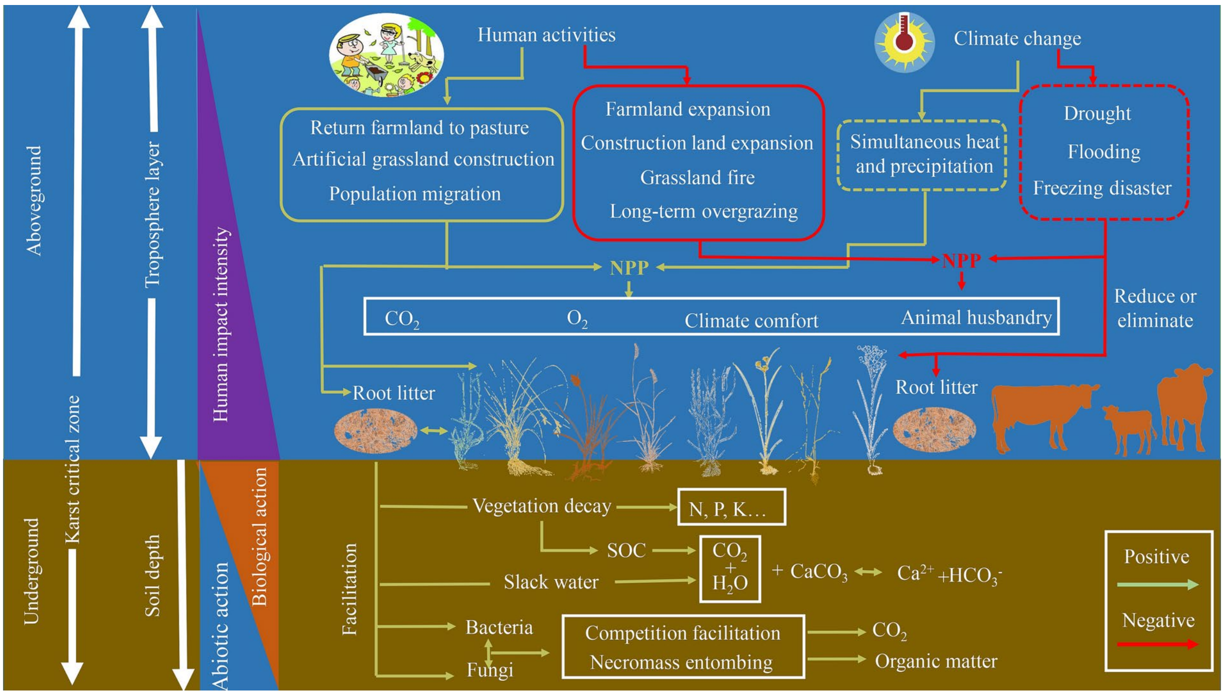

FIGURE 1
Grassland ecosystem in the KDC area.

capital to promote inclusive and green development (Zheng et al., 2019). Accordingly, researchers have paid great interest and attention to ES value accounting and value realization pathways. In understanding and valuing ES, based on a large number of ES valuation practices (Costanza et al., 1997; Díaz et al., 2018; Liu et al., 2023), the research perspective is gradually shifting from biophysical valuation, which focuses on ecological attributes and their intrinsic values, to economic attributes and their utility values (Farber et al., 2002; Jackson et al., 2016). It explored the popular accounting system of GEP (a method for summarizing the value of ES to the economy; Ouyang et al., 2020; Hao et al., 2022). In terms of ES value realization pathways, typical paths such as industrial development (Johansson, 2016), ecological equity trading (Spash, 2015), and ecological compensation (Bremer et al., 2014), etc., are explored and summarized. Moreover, researchers have carried out exploratory applications in ecosystems such as forests (Sanchez-Azofeifa et al., 2007; Gao et al., 2020), grasslands (Wu et al., 2020), and wetlands [Environmental Law Institute Research Staff (ELIRS), 2002]. Despite the extensive amount of past research, there is still a lack of systematic summarization of the value realization of grassland ES. In particular, it remains a lack of holistic knowledge about the objectives, paths, and influencing factors of grassland ES value realization. Most importantly, little is known about the value realization of grassland ES in the KDC area.

In order to provide future researchers with a summary of past results and to provide hints for next steps, this study used the Scopus database to search the literature on the value realization of grassland ES. By screening the literature according to the appropriate criteria, we identified research papers that are highly relevant to the study's topic and contain the latest findings and used content analysis to summarize the results. The research objectives of the paper are (i) to summarize the current objectives, paths, performance, influencing factors and decision-making suggestions for the value realization of global grassland ES; and (ii) to propose inspirations for the grassland in the KDC area. The results of the study are expected to increase the understanding of the realization of grassland ES value, as well as provide an important economic decision-making references for the synergy between grassland ecological protection and economic development in ecologically fragile areas.

Materials and methods

This study uses content analysis method (A literature analysis method with the advantage of transforming qualitative description into quantitative analysis; He et al., 2020; Lindgren et al., 2020) to analyze the sample literature. The content analysis method involves the following four steps: (i) determining the topic of the study; (ii) selecting a sample of literature and determining the unit of analysis; in this paper, a literature is used as the unit of analysis; (iii) literature coding and reliability testing; and (iv) statistical analysis of the coding of the literature.

Research topics

Combined with the research objectives of this paper, the research theme is defined as the value realization of grassland ES. It includes five sub-themes: the objectives, pathways, influencing factors, achievements, and recommendations.

Selection of literature sample

Literature search

The literature for this study was obtained from the Scopus database.[1] The scope of the search fields was "Title, Abstract, Keywords." For the completeness of the search literature, we considered different expressions of the search terms in the literature (Figure 2). Considering that ecological compensation and PES are two important ways to realize the value of ES (Farley and Costanza, 2010; Sonter et al., 2020), specifically included in the literature search.

Due to the variability and complexity of the languages in each country, only English literature was searched in this thesis because English is a globally used and widely understood language. Simultaneously, we select articles, reviews, and conference papers that can represent research. The range of search dates was selected from 2001 (when the MEA was launched globally) to 2 August 2023. All articles were downloaded on 2 August 2023, at which time all of the latest literature could be retrieved.

Literature screening

There are four steps in the literature selection process: (i) Literature search. After the initial search, a total of 2,707 documents were obtained. (ii) Documents deduplication. 32 duplicate documents were removed (2,675 remaining). (iii) Records screened at object level. The research object must be a grassland ecosystem. Other ecosystem types are excluded, but the complex ecosystems dominated by pastoralism (explicitly stated in the literature) are included, such as agro-pastoral, silvipasture and forest-pastoral ecosystems dominated by pastoral activities. The criteria for our selection are as follows: the title or abstract must have the expression of grassland or words directly related to grassland. The expression of grassland is shown in Figure 2, and words directly related to grassland such as livestock, grazing, pastoralist, pastoralism, herdsmen, herder, etc. At the same time, we removed the literature on seagrass ecosystems and urban grassland ecosystems because they have nothing to do with traditional grassland establishment and the development of herbivorous livestock. Based on this criterion, we excluded 1,577 papers (1,098 remaining). (iv) Records screened at text level. The selection criteria were that the core chapters of the paper must be directly related to ES value realization. The test screening criteria meet one of the following conditions: ① The research areas and cases with clear pathways (e.g., ecological compensation, PES, ecological equity trading, etc.) are essential. The literature of pure strategies and proposals was removed, such as pure proposals for grassland ES management, biodiversity conservation (or restoration) strategies, or grassland ES and human well-being enhancement. ② The Methods and Materials section provides an introduction to the pathway for realizing the value of ES, and the subsequent section has a comparison of achievements and benefits. ③ Reviews supported by case studies or case pictures of ES value realization. ④ Articles based on meta-analysis (because their

1 https://www.scopus.com

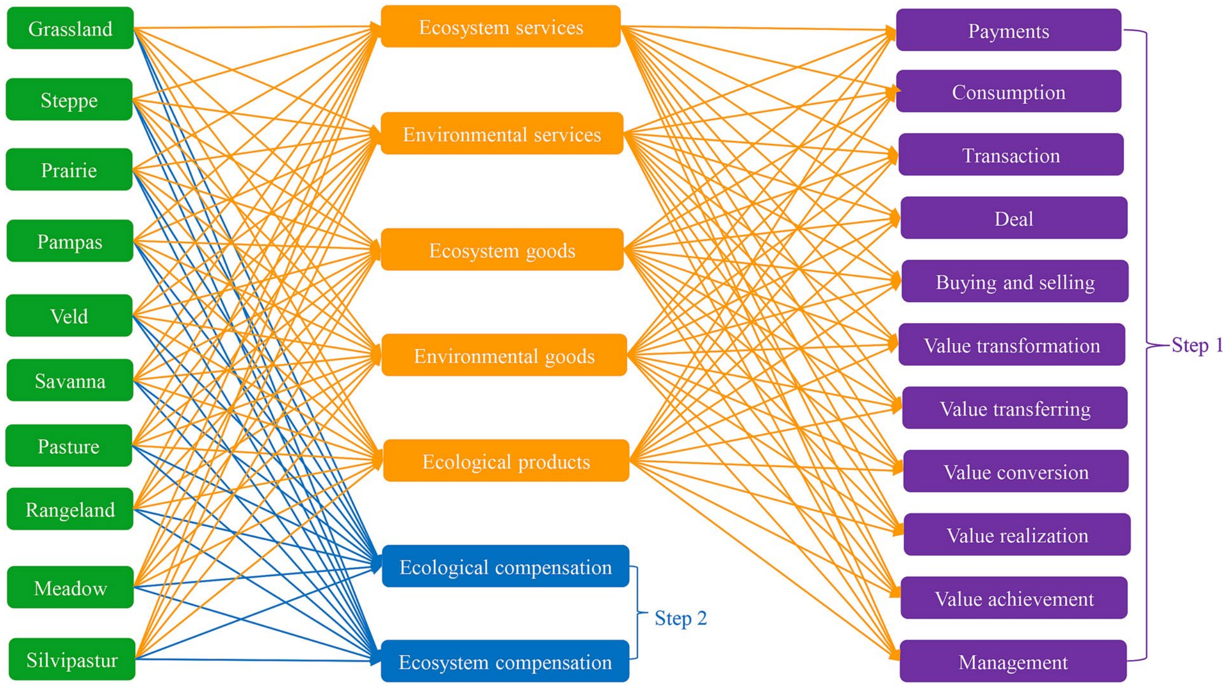

FIGURE 2
Design of search terms. The arrows represent intersection relationships.

findings are based on the synthesis of multiple cases globally or regionally and are more generalizable and instructive). Based on this, we deleted 571 literatures. Finally, we obtained 527 papers from 48 countries around the world.

Literature coding and reliability testing

Indicators and categories

The indicators and categories in this study were designed according to the study objectives. The basic principles of the design are mutual exclusion and exhaustion, i.e., the classification must be complete, thorough, and suitable for all documents, so that all documents can be classified into corresponding categories. Based on the above principles, we designed 98 analysis indicators (Table 1) on the basis of comprehensive reading of all literatures. At the same time, we classified all the indicators according to the research topics (Table 2).

Coding rules

We designed an excel sheet (see Supplementary Table 1) according to Tables 1, 2, and coded each research topic on the basis of intensive reading of each study. The test criterion for coding is whether the content of the literature discusses one or more indicators designed for each research topic. For example, whether an article has discussed the objective of realizing the value of grassland ES, combined with Table 2, we will see whether the content of the article involves one or more indicators in No. 1–15 in Table 1. We agree on rules before coding. In an article, we use "√" to indicate the indicators involved, and leave blank for the indicators not involved. It should be noted that in the achievement part of ecological product value realization, in order to reflect the current situation of the achievement, we use "↑," "↓," and "=" to indicate that the achievement is positive, negative and neutral (or invariant), respectively. To circumvent the subjectivity and arbitrariness of coding, we appointed three coders. After the first and second coders code independently, the third coder is invited to discuss and negotiate the final result for codes that disagree between them, and the final code is decided by majority consensus.

Reliability test

After coding, the average mutual agreement K_{AB} between the two coders was calculated using the Holtis formula as follows:

$$K_{AB} = \frac{2M_{AB}}{N_A + N_B} \tag{1}$$

Where, M_{AB} is the number of indicators with identical results for both coders. N_A refers to the number of indicators coded by the first coder; N_B represents the number of indicators coded by the second coder.

We used a random sampling method to select half of the literature (268 papers) and adopted Equation 1 to test the consistency of the two coders. The calculated results showed that the reliability of the interaction discriminant between the two coders was 85.54%, which can be used for the conclusion analysis.

Data analysis

Based on the indicator codes in the literature, we counted the indicators and conducted quantitative and qualitative analyses. Accordingly, we present the results in terms of the number or percentage of literature in the Results Section. In particular, it is noted that the total number of metric statistics for each subtopic may be greater than the

TABLE 1 Sample indicators.

No.	Indicators	No.	Indicators
1	Forage and grass	50	Biophysical context
2	Water supply	51	Eco-compensation standard
3	Biomass	52	Age
4	Climate comfort	53	Education
5	Pollination	54	Invested capital
6	Soil quality and health	55	Eco-compensation modes
7	Microbial communities	56	Trade-offs and synergies of ES
8	Animals	57	Land ownership
9	Plants	58	Climate change
10	Biodiversity	59	Number of laborers
11	Carbon sequestration and storage	60	Sex
12	ES	61	Employment structure
13	Water and soil retention	62	Externalities of ES
14	Pest control	63	Population size
15	Landscape and culture	64	Regional socio-economic differences
16	Environmental protection	65	Market supply & demand
17	Grass-livestock balance	66	Social relations
18	Livelihoods	67	Infrastructure
19	Poverty alleviation	68	Science and technology
20	Income	69	Scale of pasture and breeding
21	Human wellbeing	70	Social ecosystem
22	Economic development	71	Industrial upgrading
23	PES	72	Training
24	Eco-compensation	73	Environmental attitudes
25	Tax and fee management	74	Multifunctionality and complexity of grassland ecosystem
26	Trading of ecological rights and interests	75	Indigenous culture
27	Industry development	76	Credit policy
28	Grassland management	77	Product certification
29	Vegetation management	78	Breeding management
30	Graze management	79	Plant community configuration
31	Breeding management	80	Plant species selection and breeding
32	Breeding efficiency	81	Carrying capacity of livestock
33	Grassland quantity or quality	82	Time gradient of grazing
34	Grazing rates	83	Population management of grazing
35	Pollution control	84	Mowing and pruning
36	Habitat	85	Fertilization management
37	The species pool	86	Optimize landscape patterns
38	The species intensity	87	Pesticides management
39	The species richness and abundance	88	Fencing management
40	Quality of life	89	Soil texture improvement
41	Social stability	90	Infrastructure construction
42	Income and expenditure structure	91	Tillage management
43	Resident's deposits	92	Natural recovery
44	Willingness and preference	93	Rotation management
45	Cognition and values	94	Fire management
46	Supervision	95	Hunting management
47	Land use pattern	96	Invasive species management
48	Costs and benefits	97	Water regulation
49	Policy instruments	98	Objective design

TABLE 2 Classification of indicator categories.

Sub-topics	Index no.
(I) The objectives of ES value realization	1–22
(II) The pathways of ES value realization	23–31
(III) The achievements of ES value realization	1–22, 32–43
(IV) Influencing factors of ES value realization	44–70
(VI) Recommendations of ES value realization	28–31, 46–49, 51, 53–55, 57, 66–68, 71–98

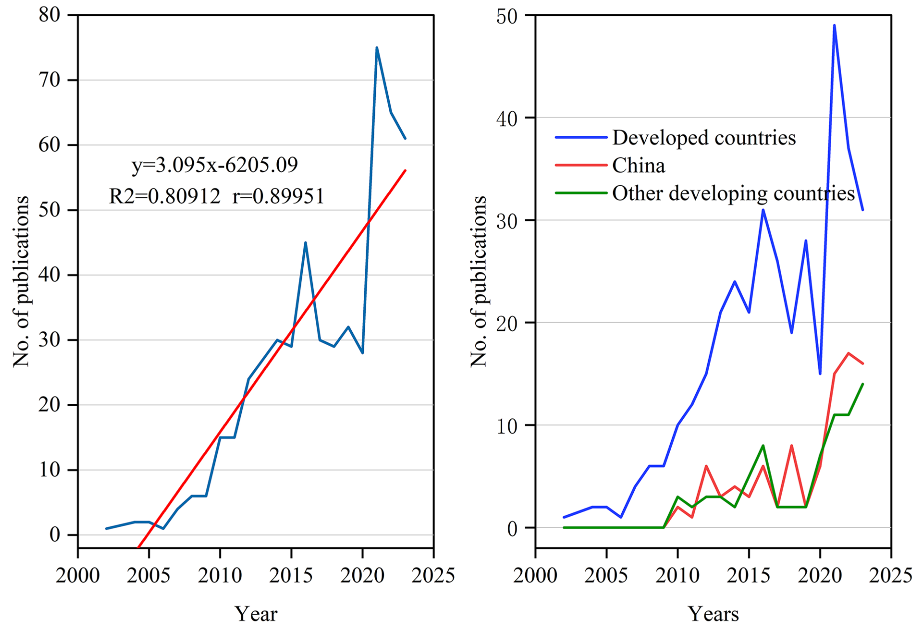

FIGURE 3
Year and country distribution.

total number of literatures, the reason being that an article will include multiple metrics per subtopic. For example, in one article, multiple goals such as biodiversity conservation, carbon sequestration, and income increase co-exist. For this reason, the percentage of the indicator in the following is the ratio of the number of the indicator to the total number (527 studies). Finally, we used Origin 2021 for data visualization.

In combination with the indicator statistics, our intention is to make the following three aspects of content analysis: (i) Bibliometric analysis (include year of publication, research sites, and country of the first author) to investigate the research status quo. Especially, we can understand the hot and cold spots areas of the world. (ii) Summarize the current understandings, practices, achievements, causes, and recommendations for realizing the value of grassland ES globally, and identify knowledge gaps to seek breakthroughs for future research. (iii) Discuss the inspiration to identify priorities for grassland ecosystem conservation coupled with economic development in the KDC area.

Results

Literature distribution

The literature has shown a fluctuating growth since 2001. As noted, 527 studies published between 2001 and 2023 met our screening criteria. In 2001–2012 (the initial phase), the number of studies was 76, accounting for 14.42% of the total. In the following 10 years (the fast developing stage), the number of studies showed a fluctuating growth trend, with about 40 studies published annually. The total number of studies published reached 451 (85.58%). Especially from 2021 to 2023, the number of articles published shows a rapid growth trend, with more than 60 studies published annually (Figure 3).

Literature mainly from economically developed countries with abundant grassland resources. The literature samples are from 48 countries around the world. Among them, the literatures from developed countries and developing countries accounted for 68.31 and 31.69% of the total, respectively. Among specific countries, the United States of America and China ranked the top two in terms of number of publications, accounting for 22.39 and 17.27% of the total, respectively. This was followed by United Kingdom (6.45%), Germany (5.12%), Australia (3.04%), France (2.85%), Switzerland (2.66%), and Brazil (2.66%). The remaining countries had a smaller proportion of literatures, all less than 0.95% of the total (Figure 4A).

The study area located in 70 countries globally, but the distribution was uneven. In general, the study area was mainly distributed westward from China to the Mediterranean coast and the United States of America. Meanwhile, countries in the Southern Hemisphere, such as Brazil, Australia, and Argentina, etc. were also hot research areas (Figure 4B). The study area of 17.65% of the literature was in China,

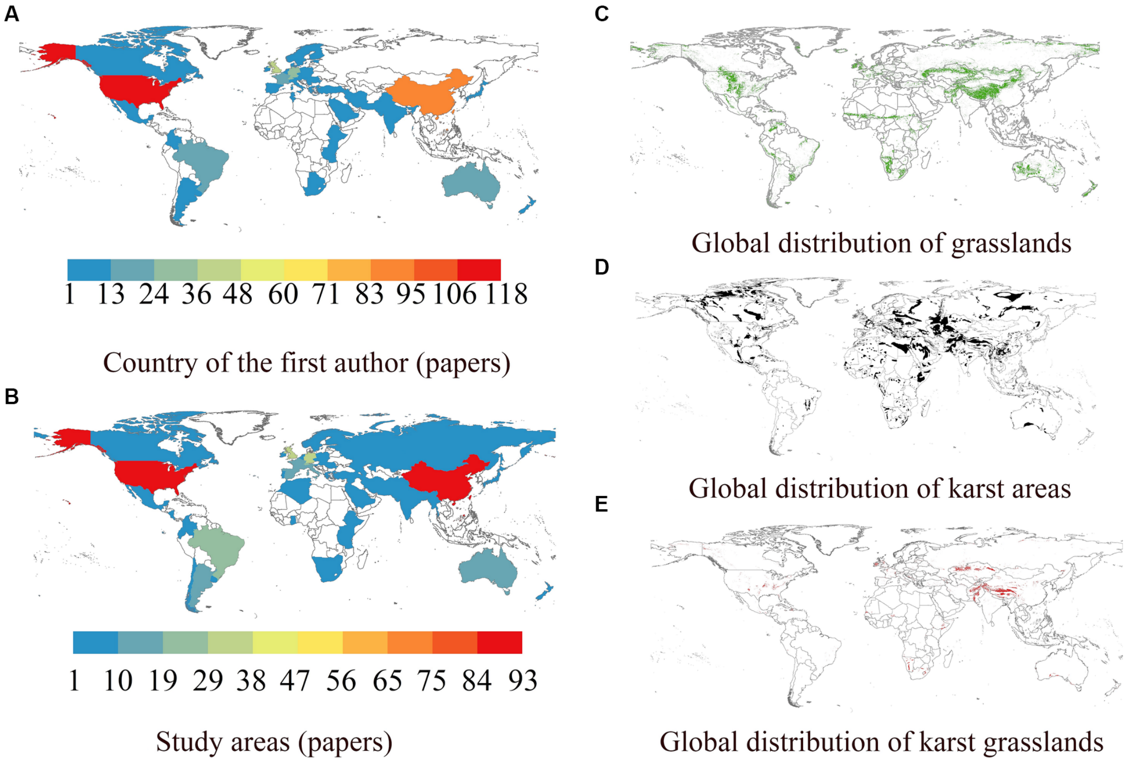

FIGURE 4
Distribution of publications, study areas, grasslands, karst areas, and karst grasslands. **(A)** Statistics on the country of the first author based on the number of documents. **(B)** Statistics on the countries in which the study area is located based on the number of documents. **(C)** Global distribution of grasslands. **(D)** Global distribution of karst areas. **(E)** Global distribution of karst grasslands. The grassland data was extracted from http://maps.elie.ucl.ac.be/CCI, and the karst data from https://www.fos.auckland.ac.nz/our_research/karst/index.html.

followed by the United States (16.13%), United Kingdom (6.26%), Germany (5.5%), Switzerland (4.74%) and Brazil (4.18%). In addition, a significant portion of the study area (9.49%) is transboundary. There are relatively few study areas from countries in Africa and Central Asia.

Objectives of realizing the grassland ES value

Enhancing ES and human well-being received widespread attention globally. In terms of ES improvement. Biodiversity has received much attention worldwide (53.42%, among them, 20.49%, 19.17%, 6.26%, and 3.8% of the total number of papers focused on animal, plant, microbial diversity, and habitats, respectively). Followed by biomass improvement (19.54%), carbon sequestration and storage (18.79%), and grassland resource and environmental protection (10.63%). Not to be overlooked, the improvement of soil fertility and health has also received some attention and is supported by 12.33% of the papers. In comparison, climate regulation, pest and disease control, and resources and energy conservation received less attention, accounting for 0.38%, 0.95%, and 1.14% of the total papers, respectively. In terms of improving human well-being, 9.49% of papers considered that the objectives were to improve people's incomes. 4.93% and 0.76% of the total papers aimed at livelihoods and poverty alleviation, respectively.

Cognition varies greatly among countries. Developed countries attach importance to the improvement of ES, while developing countries are more inclined to livelihood improvement and grassland resource protection (Figure 5). Take developed countries as examples, in the United States, carbon sequestration and storage (25), biodiversity conservation and restoration (24), biomass improvement (22), income (15), and grassland resources and environmental protection (14) received high attention. In Europe (taking the number of literature from Switzerland, UK, Germany, France, Italy), biodiversity is a research hotspot (93 papers, among them, 37, 36, 12, and 8 papers focusing on the conservation of animal, plant, microbial, and habitat diversity, respectively.). Close behind are carbon sequestration (25), biomass (25), soil quality and health enhancement (25). Nevertheless, grassland resources and environmental protection (28), botanical diversity (19), biomass enhancement (23), income (16), soil quality and health (15), and carbon sequestration and storage (15) are the important objectives in BRICS countries (Brazil, Russia, India, China and South Africa). In other developing countries, perceptions of the objectives for realizing the value of grassland ES vary widely. For instance, Argentina is concerned with biodiversity and carbon sequestration, soil quality and health; Colombia is more concerned with food and raw materials; and Ethiopia is concerned with carbon sequestration and biomass enhancement.

Pathways of realizing the grassland ES value

Grassland management and PES being the most widely used. Combined with the goal of realizing the value of grassland ES, six paths of grassland management, PES (or ecological compensation), industrial development, trading of ecological rights and benefits, tax administration, and ecological engineering were explored globally.

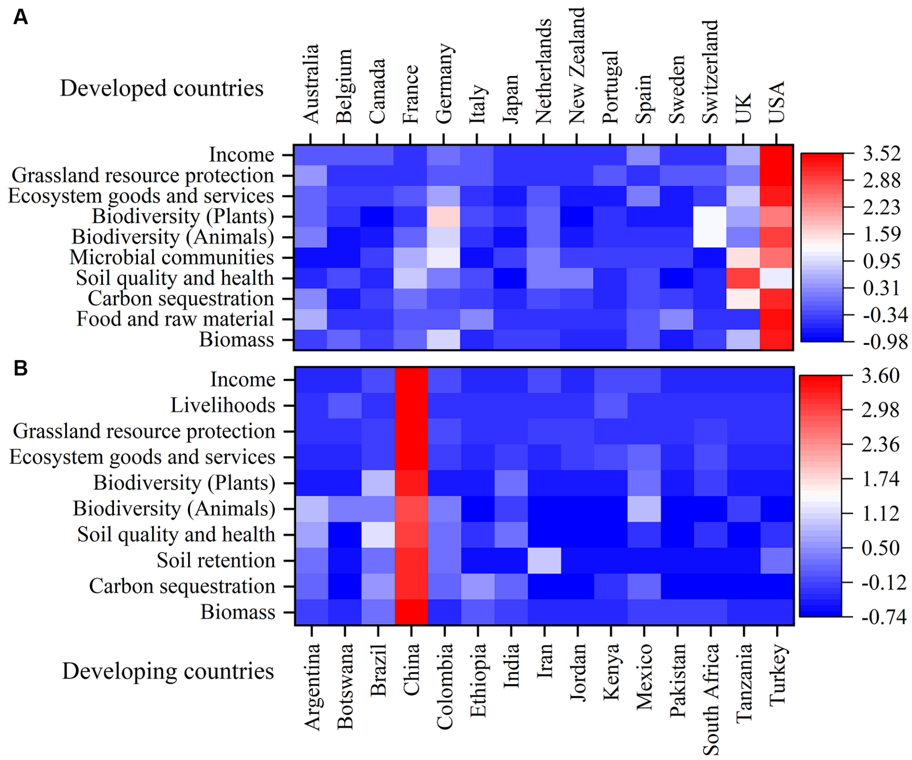

FIGURE 5
The objectives of grassland ES value realization in different countries. **(A)** The objectives (Top 10) in developed countries (Top 15). **(B)** The objectives (Top 10) in developing countries (Top 15). Statistics based on the number of documents.

Among them, grassland management is the most common and popular practice worldwide, accounted for the 67.74% of the total studies. 27.13% of the studies selected PES (or ecological compensation). There were fewer studies on industrial development, trading of ecological rights and benefits, grassland engineering, and tax administration, accounting for 7.02%, 1.9%, 0.95%, and 0.19% of the total, respectively.

Progress in exploring pathways varies across countries. Grassland management is widely practiced in 41 countries (91.67% of the total number of countries selected) with the aim of improving the direct provision of ES. At the same time, PES (or ecological compensation) provide a welcome route and is widely used worldwide, among which the top five countries are China (45), United States of America (34), Switzerland (13), United Kingdom (11), Australia (8). The industrial development paths are practiced in both developed and developing countries, the developed countries are United States of America (8), Australia (3), Spain (3), etc.; the developing countries such as China (5), Iran (3), Brazil (2), India (1), etc. Grassland engineering measures are more prevalent in countries such as the United States, the Netherlands, and China. The eco-equity trading pathway is mainly practiced in developed countries (8) and China (2). The tax administration path is minimal (1) and come from the case of carbon trading in Sweden.

Achievements of realizing the grassland ES value

Significant achievements have been made. Literature statistics showed that the realization of the grassland ES value improves the productivity and provisioning capacity of ES, increases the income of relevant stakeholders and protects grassland resources and the environment. For example, most of the literature contends that value realization of ES enhances grassland ES such as biodiversity (153), carbon sequestration (62), biomass (50), soil quality and health (42). In particular, important achievements have been made in diversity conservation of animals (64), plants (55) and even microorganisms (17), habitats (14), and species pools (3). Meanwhile, a substantial amount of literature highlights that the value realization of grassland ES also serves a vital role in enhancing the livelihoods (12) and boosting the earnings of farmers (45).

There are some negative and neutral (or unimproved) outcomes. Some literature indicates that realizing the value of grassland ES is an imperfect pathway, or the desired outcomes have not been met in some fields. For instance, 14, 13, 13, and 10 papers, respectively, found that counterproductive measures of grassland ES value realization had adverse effects on biomass increase, soil quality and health improvement, grazing rate reduction, and carbon sequestration. Meanwhile, 69 papers indicated unconspicuous results or undesirable outcomes (Figure 6).

Influencing factors of grassland ES value realization

Stakeholders or right-holders are the primary influencing factors. The literature statistics show that there is a general global focus on the impact of pastoralists' grassland management approach and intensity (324). This is closely followed by herders' willingness and preferences

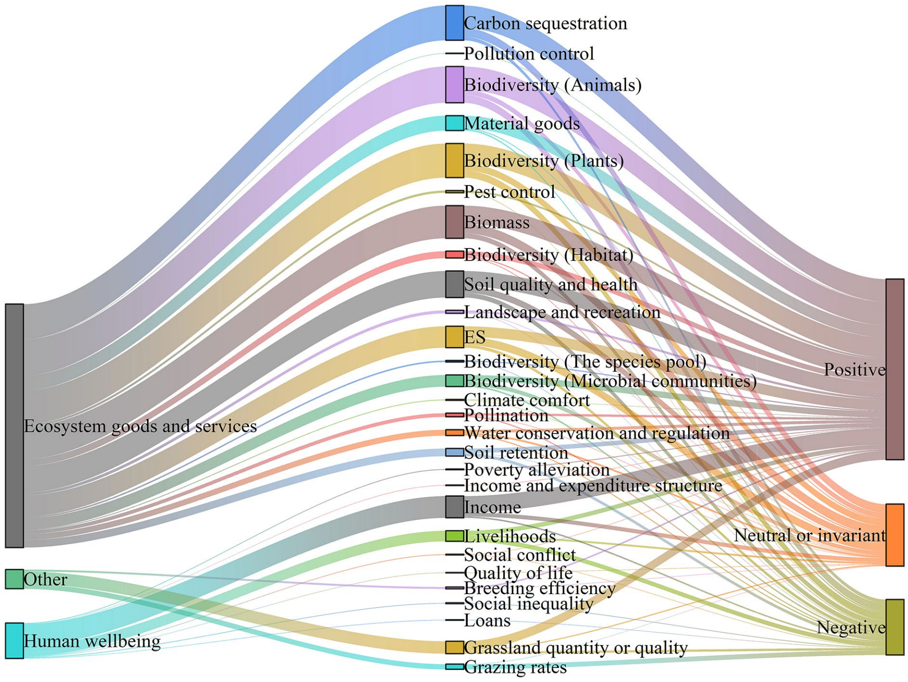

FIGURE 6
Achievements of grassland ES value realization.

(43), land use patterns (36), cognition and values (35), and income (28). In addition, some factors should not be neglected, such as herders' education level (11), quantity of number (6), labor employment structure (5), number of family members (3), and social relations (2), etc.

Natural, governmental, and socio-economic factors also hold significance. In terms of natural factors, most of the literature focuses on the impacts of the biophysical context of grasslands (137), the trade-offs and synergy in ES (125), and climate change (40). A small portion of the literature discusses the biological invasions (10) and the externalities of ES (6). In addition to the natural factors, the role of government is a prevalent concern among researchers. 22, 18, and 17 papers, respectively, have concluded that the application of the ecological compensation standards, supervision and policy instruments set by the government affect the performance of value realization of grassland ES. Moreover, the influence of government capital investment, land ownership design, and ecological compensation methods is significant. Socioeconomic factors, such as regional socio-economic differences, market supply and demand, science and technology, etc., were supported by less than 5 papers (Figure 7).

Recommendations for realizing the value of grassland ES

Most studies advocate optimizing grassland management. Considering the gap between the reality and the goal of the value realization of grassland ES, combined with the analysis of influencing factors, a significant amount literature advocates for the requirement of effective tactics for grassland management. 270, 214,163, 12 studies suggested optimizing the management of grazing, grassland rehabilitation, vegetation establishment and breeding, respectively. Among the specific indicators, the top five strategies were grazing carrying capacity design (169), plant community configuration (87), grazing time gradient (80), plant species selection and breeding (74), and mowing and pruning (52). Moreover, there was also a prevalent literature on strategies like fertilizer management (45), optimizing landscape patterns (32), managing fire (25), optimizing livestock breeding management (12), and managing pesticide (12), etc.

Optimizing policy decisions is critical. The number of literatures suggesting the design of reasonable eco-compensation standards (52), the optimization of existing policies (51), the establishment of scientific targets (47), the implementation of flexible eco-compensation methods (42), and the implementation of industrial upgrading (27) ranked among the top five. At the same time, some literature suggested the importance of increasing financial investment (19), optimizing production-living-ecological space (17), implementing flexible government supervision (13), and conducting the eco-products certification and right confirmation (3).

The stakeholders or right-holders engagement is equally important. 76 papers contend that optimizing the land use patterns of pastoralists is crucial, while 56 papers stress the importance of taking into account factors specific to the pastoralists themselves (e.g., demographics, income and expenditure structure, and age structure, etc.). In addition, a number of other recommendations are irreplaceable, such as alternative livelihoods (30), respecting for local values (13), the application of new technologies (11), and strengthening education and training (8), and so on (Figure 8).

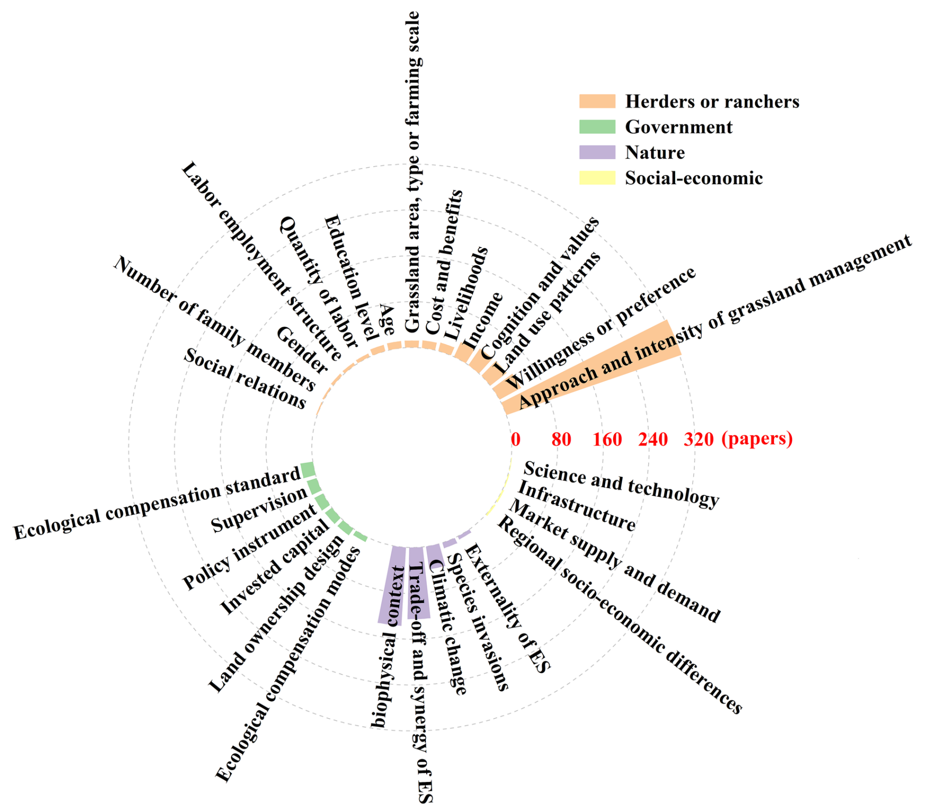

FIGURE 7
Influencing factors of grassland ES value realization.

Discussion

Research and development status of the value realization of grassland ES

Since the global launch of the MEA in 2001 [Millennium Ecosystem Assessment (MEA), 2005], how to protect fragile and degraded ecological environments, enhance the ES productivity, and develop a green economy has become a pressing global need. During 2001–2012, developed countries represented by the European Union have carried out a large number of exploration on the realization of grassland ES value. For example, the Agri-environment schemes implemented by European Union countries aim to energize the environmentally friendly practices (Aviron et al., 2007; Ansell et al., 2016). Since 2012, a large number of research results from developing countries have emerged, fueling the trend of rapid growth in research results. Developing countries, as regions where current problems of grassland ecosystem conservation and economic development are prominent, need to find localized solutions and integrate a large number of achievements in recent years. For instance, after the Chinese government incorporated ecological civilization into its national strategy, a large number of ecological projects have been implemented in the grasslands of northern China (e.g., Inner Mongolia region; Fu et al., 2023), and a large number of research results have been obtained. A large number of studies of silvipasture systems on soil fertility and health have been conducted in countries such as India, with remarkable results (Ramakrishnan et al., 2021; Halli et al., 2022).

Currently, the literatures and study areas are mainly distributed in a few countries. on the one hand, these countries have vast grassland resources. For example, the Central Great Plains in the United States, along the Alps in Europe, eastern and western Australia, and the Qinghai-Tibet Plateau and Inner Mongolia Plateau in China are all major grassland distribution areas in the world (Figure 4C). Moreover, the livestock industry in these regions is more developed globally. On the other hand, these countries have unparalleled advantages over other countries around the world in terms of capital, talent and scientific research strength. For instance, the Western Europe, the United States and Australia are developed countries; China, India, Brazil, and other emerging developing countries have significant economies. The advantages of grassland resources and economic strength elucidated the spatial distribution pattern of literature and research areas.

However, the spatial mismatch between economic (or scientific) strengths and the distribution of grasslands, or language constraints (only literature in English was considered in this paper), has resulted in an underrepresentation of literature on a portion of typical grasslands around the globe. For example, there are few studies on Arctic alpine grasslands in Russia, temperate grasslands in Central Asia, tropical savannas in Central and Southern Africa. More regrettably, little research literature has focused on karst areas (especially karst desertification areas), even if karst is an important component of global terrestrial ecosystems (Figure 4D), karst grasslands are widely distributed around the world (Figure 4E; Supplementary Table 1) and play an irreplaceable role in maintaining ecological health, improving farmers' livelihoods, coping with climate change, and conserving biodiversity. Future research

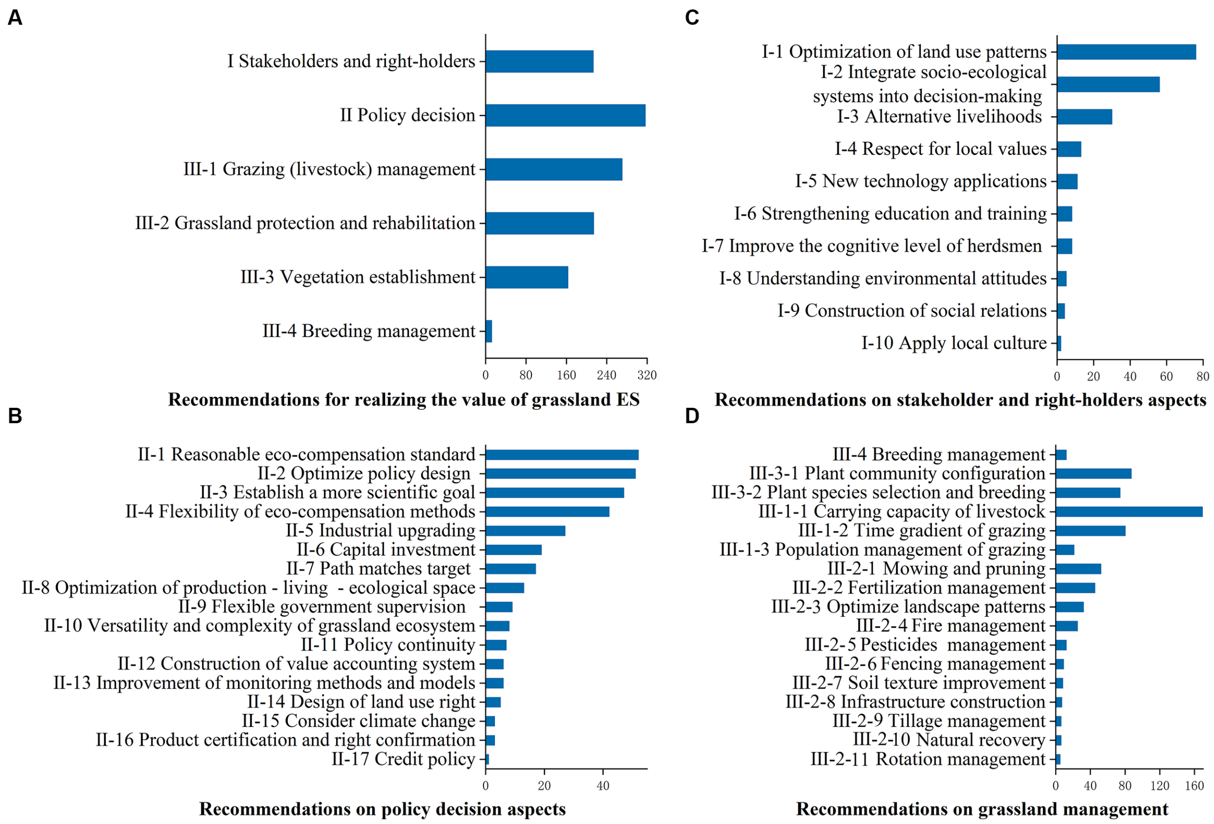

FIGURE 8
Recommendations for the value realization of grassland ES. **(A)** Three broad categories of recommendations, of which the third category includes four subcategories. **(B)** Ranking of policy decision recommendations. **(C)** Recommendation ranking of stakeholder and right-holders. **(D)** Recommendation ranking of grassland management (four subtypes).

should focus on currently neglected areas based on the principles of representativeness, typicality and wholeness in the selection of global grassland study areas. In particular, karst grasslands should be given the attention they deserve. Correspondingly, based on the characteristics of diverse karst types and prominent spatial heterogeneity (Gao et al., 2021; Bátori et al., 2023), we should explore the mechanisms for realizing the value of grassland ES under different landscape types, different grades of karst desertification, different climatic conditions, and different socioeconomic backgrounds, and provide selective solutions for ecosystem restoration and industrial green development.

Objectives and vision of the grassland ES value realization

Currently, it has become a global consensus to enhance ES by protecting and restoring the grassland ecosystems and improve human well-being through greening of the economy (Kemp et al., 2013). In terms of the improvement of ES, scholars and government policymakers are generally concerned with grassland biodiversity, carbon sequestration, and material goods, which is basically consistent with the global understanding of the main functions of grassland ecosystems (Zhao et al., 2020). At the same time, considering the fragile ecological environment and limited livelihoods in pastoral areas, researchers generally recognized the importance of protecting grassland resources and the environment through grass-livestock balance while improving the livelihoods of pastoralists (Hou et al., 2021). In this context, livelihoods and incomes of pastoralists and regional socio-economic development have received much attention. The national conditions (e.g., grassland resource endowment, environmental awareness, economic strength, etc.) vary widely, and the goal of realizing the value of grassland ES in each country is obviously different. Developed countries (such as the European Union, the United States, Australia, etc.) generally regard ES (e.g., biodiversity, carbon sequestration, soil health, etc.) as the greatest wealth of humanity (even though these services that are difficult to trade on a private markets). Therefore, these countries generally pay attention to the conservation of biodiversity and the productivity of ecosystem regulating services (Chomel et al., 2022). However, developing countries are generally concerned with the soil health, the provision of ecological material goods, the ecological protection of degraded grasslands and the enhancement of herders' livelihoods due to high population pressure and limited livelihoods in pastoral areas (Baradwal et al., 2022, 2023; Li C. et al., 2023). In developing countries, the protection of grassland resources for the provision of ecological goods and services is currently considered an urgent task. On the one hand, these goods and services can not only be traded in private markets, but also directly improve the income and livelihood of pastoralists. On the other hand, by improving the livelihood, the disturbance of human activities on grassland can be reduced, and a virtuous cycle of grassland resource conservation and livelihood improvement can be realized.

About 20 years of global practice have proven that the realization of the value of grassland ES has played a positive role in the conservation of grassland resources, the restoration of biodiversity (Kampmann et al., 2012), the enhancement of the supply of ecosystem goods and services (Chamberlain et al., 2017; Varsha et al., 2019), the increase of herders' incomes and the improvement of herders' livelihoods (Louhaichi et al., 2016; Huang et al., 2018). However, there are some unsuccessful cases. One is that the realization of the value of grassland ES has not reached the intended goal. For example, in the Netherlands, the Agri-environment schemes are also not effective in protecting biodiversity (Kleijn et al., 2001). In Davos (Switzerland), grazing has a negative impact on plant richness and agricultural quality (Fischer and Wipf, 2002). Research has shown that ecological compensation measures have not effectively reduced grazing rates in some areas of China (e.g., Sichuan Province, Inner Mongolia Autonomous Region; Wilkes and Tan, 2010; Byrne et al., 2020), and some measures have even exacerbated predatory grassland development (Li et al., 2018; Liu et al., 2021). The second is associated with some economic and social problems. For instance, in Inner Mongolia, China, ecological compensation of grasslands has spawned social conflict and social inequality (Li et al., 2015). Third, there is a trade-off between ecology and economy. Par example in Costa Rica, the government promoted conservation of grassland ecosystems by establishing rangeland management and banning beekeeping in national parks and reserves, while limiting beekeepers' livelihoods (Galbraith et al., 2017).

Theoretically, grassland ES value realization aims to synergistically enhance ES and human well-being through ecosystem restoration and greening of the economy. Nevertheless, the current research generally emphasizes ecological protection over economic development, or attaches importance to economic development over ecological protection. There are few cases of coordination between ecological protection and economic development. To this end, the next step should be to maximize the production capacity of grassland ES and increase the flow of ES from supply to human consumption on the basis of maintaining the diversity, stability and sustainability of grassland ecosystems. Meanwhile, a comprehensive evaluation system based on ecosystem health, ecological product supply, green economic output, and economic system feedback should be established. More importantly, based on the valuation of grassland ES and the exploration of the paths of ecological industrialization and industrial ecologization, the value realization rate of grassland ES (the ratio of the realized ES value to the total value), the industrial transformation rate (the contribution rate of the ES value to GDP), and the feedback rate of the economic system (the input proportion of GDP used for ecosystem protection and restoration) should be improved. Finally, a virtuous cycle model of grassland ecosystem protection-ES supply-monetary value realization-economic system feedback should be constructed.

Path exploration and optimization for the value realization of grassland ES

Grassland management is an applicable pathway for enhancing productive capacity based on the supply side of ES, and is widely practiced globally. This pathway is based on "natural law + artificial assistance or regulation," using grazing, mowing, fertilizing, etc., to maintain ecosystem health and enhance the provision of ecosystem goods and services (Van Vooren et al., 2018). However, this path is constrained by ES trade-offs. For example, fencing and grazing bans are good for biodiversity conservation, water conservation, and soil retention (Liu et al., 2022), but they can cause herders to lose income. Another example, the esthetic value of the landscape may be compromised for the sake of grass forage production (Neyret et al., 2021). This requires making decisions about ES based on the needs of both humans and ecosystems. However, grasslands are complex ecosystems with complex feedbacks between elements within the system rather than a single cause-and-effect relationship (Moreno-Mateos et al., 2020), and human preferences for ES may lead to ecosystem degradation. Therefore, it is necessary to improve the productivity of ES by optimizing grassland management practices based on ecosystem health.

PES (or eco-compensation), a pathway adopted by most countries, aims to economically subsidize stakeholders or rights-holders in order to increase their incomes or reduce their losses. For example, the PES program in European Union aims to financially compensate farmers and herders for any loss of income due to measures that benefit the environment or biodiversity (Kleijn and Sutherland, 2003). In China, the government guide herders to reduce grazing rates to protect grassland resources through ecological compensation (Hu et al., 2019). However, the path is dominated by government investment (a model that often lacks sustainability), and is often criticized for low compensation standards and unreasonable compensation methods (Adamowicz et al., 2019; Behrendt et al., 2022). Hence, it is extremely crucial to improve the mechanism of ecological protection compensation and damage compensation (Salzman et al., 2018). For instance, the value of ecosystem goods and services is used as a compensation criterion to enhance the "sense of gain" of stakeholders. At the same time, according to the differentiated needs of relevant stakeholders, establish an ecological compensation mode that integrates funds, technology, materials and services.

As a traditional pathway, industrial development aims to enhance human well-being and protect grassland resources through comprehensive consideration of ecological carrying capacity and efficient resource utilization. For example, the more globally prevalent model of livestock mobility (Mousavi et al., 2020; Barry, 2021), intensification of rangelands (Cortner et al., 2019). This path, although it is easy to increase the income of stakeholders in the short term, is prone to cause ecological damage (Yang et al., 2023). In addition, the path still faces the dilemma of traditional development mode, short industrial chain and low degree of industrial integration development. To strengthen these weaknesses, on the one hand, the supply capacity of ES should be improved. For example, the production of ecosystem goods and services should be enhanced by relying on the cultivation of grassland pioneer species, the optimal allocation of communities, and the optimization of ecosystem structure and function. On the other hand, we should strengthen the research and development of new products, extend the industrial chain, and rely on brands to enhance added value around the transaction and consumption process. Through the improvement of quality and efficiency on the production side and the increase of added value on the consumption side, the green transformation and upgrading of the industry can be promoted.

In addition, there are some pathways that are highly sought after by the government and academia. For example, the transaction of ecological rights and interests internalizes the externality of environmental protection benefits through linkages such as rights confirmation, pricing, and transaction. Examples include efforts in the United States to develop a voluntary carbon credit and trading market (Booker et al., 2013) and the Perbrink project to create a market for privately provided ES (Chakrabarti et al., 2019). Besides, tax administration has become an option for realizing the value of grassland ES. Typical cases such as Sweden, which has explored a climate tax on food consumption and returned the tax to farmers to enhance grassland biodiversity (Gren et al., 2021). However, eco-equity trading, tax and fee administration has only been piloted on a small scale and is far from being rolled out globally. The reason is that the current market transaction and tax management mechanism is not perfect, and the market is sluggish. The next step should be to strengthen market cultivation and optimize government management to achieve the goal of consumers paying for ES and producers getting returns.

Dilemmas and recommendations for realizing the value grassland ES

Several dilemmas require attention to bridge the gap between the performance and targets for realizing the value of grassland ES. First and foremost, the cognition and practice of stakeholders or rights holders are far from the original intention of ecosystem protection and restoration. Previous studies have shown that herders or ranchers' culture, knowledge (Tang et al., 2022), preferences (Clot and Stanton, 2014; cortés-Capano et al., 2021), values, and trust in ecological protection projects (Farley et al., 2011) directly or indirectly affect the effectiveness of ecological protection and restoration of grasslands. Furthermore, the household size, labor force, age, gender, employment, and income expenditure structure of herders or ranchers result in different livelihood sources, coupled with spatial heterogeneity in grassland size and land productivity, leading to different patterns of grassland resource use (Richards et al., 2017). When stakeholders or rights holders engage in production activities with the primary goal of enhancing their livelihoods, their production behavior may destroy grassland resources. Second, there is a trade-off between government and stakeholders (or rights holders) in the demand for ES. The former tends to promote grassland biodiversity and ecosystem regulatory services in the public interest, while the latter tends to increase revenue based on private equity (e.g., in the case of spatial conflict between wild and domestic herbivore populations in African savannas; Fynn et al., 2016). If the government and stakeholders cannot reach agreement on competitive demand, this will often result in a large reduction in the performance of grassland ES value realization. For example, in PES practice, there is a large gap between government ecological compensation standards (or compensation methods) and herders' expectations, resulting in ecological compensation failing to meet specified targets (Jack et al., 2008; Addison and Greiner, 2016). Stakeholders are resistant to mandatory government oversight, which has reduced herders' participation in ecological conservation projects to some degree (Olenick et al., 2005; Roche et al., 2021). Finally, and most importantly, grassland ES have the fundamental characteristics of publicness and externalities, and the industries they form also have positive externalities. The tragedy of the commons is triggered by the fact that public ES are difficult to trade in private markets and can be exploited by any stakeholder at no or low cost.

To address these obstacles and bottlenecks, a government-led, relevant stakeholder-participation and market-oriented mechanism should be established. Primarily, stakeholder and right-holder engagement. The stakeholders (or right-holders) are not only the providers of ES, but also an important force for ecosystem protection and restoration (or resource destruction). It is necessary to provide equal and inclusive participation opportunities for the stakeholders (or right-holders; including underrepresented groups), to adopt their local knowledge, skills and experiences, and to respect their local culture, cognition and values. All the stakeholders (or right-holders) should enjoy equal and fair benefit distribution of the dividends of "greening." Especially, it is important to seek substitutive livelihoods for the stakeholders (or right-holders) to enhance their income and quality of life. Second, the implementation of the main responsibility of the government should be the priority. The government, as the manager of public services and the main consumer of ES (especially public ES), should make full use of its management functions to create the conditions for converting ES into assets, and ecological assets into capital, by solving the neck-jamming difficulties of ES, such as right confirmation, certification, pricing, trading and supervision. Equally important, the government should also increase public investment in purchasing ES and providing feedback to nature through projects for restoring and protecting ecosystems. Finally, cultivate the private market. ES are the necessities of human life, just like industrial or agricultural products. When the beautiful ecological environment becomes scarce (Kinzig et al., 2011), market consumption becomes possible. The supply and demand structure should be regulated according to the different types of consumption of grassland ES (subsistence, developmental, hedonic, etc.) to stimulate market vitality.

Inspiration for the grassland in the KDC area

Grassland in the KDC area has both ecological and economic attributes. On the one hand, grasslands are an inevitable stage of succession from barren gravel land to forest (Xiao et al., 2019). Bare or degraded grasslands can be revegetated to maintain ecosystem health and increase the provision of ES (Qiao et al., 2021). On the other hand, grasslands have an important forage value and are often considered an important starting point for industrial restructuring (Li Y. et al., 2023). However, the fragility of ecosystems, coupled with high population pressures for survival and development, urgently requires ecological and economic compatibility. The experience and lessons learned from the value realization of the global grassland ES can provide the following insights for grasslands in the KDC area:

1. Vision and objectives. Grassland in the KDC area aims to provide an ecological security shield for regional economic and social development, while improving human well-being through the development of grassland animal husbandry. We should adhere to the principle of ecological priority and take the route of industrial ecology based on ecological carrying capacity.
2. Paths. First, based on the fundamental characteristic of the fragile, vulnerable and sensitive of the grassland ecosystem in the KDC area, we should enhance the productivity and supply capacity of ES (including type, quantity, and quality) by

optimizing ecosystem functions, while combining ecosystem composition, structure and process and taking into account the ecological carrying capacity and ecological security pattern. Second, both the two instruments of government and market should be used to realize the monetary value of ES. Particularly, we should transform the value of public ES by turning ecological resources into assets and ecological assets into capital. Third, we should improve the ecosystem protection compensation and damage compensation mechanism of grassland ecosystems in the KDC area.

3. Emphasis. Due to the high population density in areas of KDC, it is crucial to prioritize the livelihood of stakeholders, while also seeking to protect the grassland ecosystem. To this end, stakeholders and right-holders should be guided to participate in ecosystem conservation based on the search for alternative livelihoods and the upgrading of herbivorous animal husbandry. Accordingly, governments should play the role of public administrators to facilitate the trading of ES through the assetization of ecological resources, and increase financial inputs based on the role of ES consumers. More importantly, there must be a mechanism for feedback from the economic system to ecosystem on the basis of industrial development.

Conclusion

We selected 527 papers from 48 countries worldwide over the last 20 years based on the Scopus database. The content analysis method was used to analyze (quantitatively or qualitatively) the current research situations, landmark achievements and limitations of global grassland ES value realization, and accordingly, the inspiration for grassland in the KDC area was enlightened. There are following findings:

The literature on realizing the value of grassland ES showed a fluctuating growth trend from 2001–2023, with slower growth in the 12 years following the MEA and faster growth since 2013. The number of publications and study areas are mainly distributed in developed countries or emerging economies countries with rich grassland resources. Grassland management and PES schemes are widely used around the world to improve grassland ES productivity, farmer's incomes and livelihoods. Developed countries generally pay attention to the conservation and restoration of grassland biodiversity, while developing countries focus more on protecting grassland ecosystems by reducing grazing rates to increase herders' incomes and improve their livelihoods. Ecological equity trading and tax management are also important ways to realize the value of grassland ES, but they are mainly used in developed countries and are still in the exploratory phase. Global practice shows that grassland ES value realization has widely enhanced ES (e.g., biodiversity, carbon sequestration, soil quality and health, etc.) and improved human well-being (e.g., income, livelihoods, poverty alleviation, etc.), but there are also cases of failure or imperfection (e.g., grazing rates did not decrease, herders increased their loans, etc.). The performance of the value realization of grassland ES is affected by stakeholders (or right holders), government policies, nature and socio-economic. Among them, grassland management methods and intensity, the stakeholders (or right holders) willingness or preferences, the government ecological compensation standards and methods, the biophysical context, and the trade-off of ES are crucial. Researchers strongly recommend optimizing grassland management (e.g., suitable grazing, mowing, fertilization, etc.), policy design (e.g., improve the compensation standard and optimize the compensation method), and guiding stakeholders engagement (e.g., adopt their local knowledge, skills and experiences, and respect their local culture, cognition and values.) around the objectives, pathways, and influencing factors.

Nevertheless, there are also some shortcomings and dilemmas that need to be addressed. For example, some grasslands of high global interest (e.g., Arctic alpine grasslands, savannas, pampas, karst grasslands, etc.) are underrepresented in the literature. There remains a lack of effective pathway for public value realization of grassland ES. The linkage mechanisms of "grassland ES-industry development-economic system feedback-ecosystem protection" remains unclear. Next step, the selection of study areas should be optimized based on the principles of representativeness, typicality, and completeness. Additionally, a government-led, relevant stakeholder-participation and market-oriented mechanism should be established.

Based on the above findings, we propose that, the goal of realizing the value of grassland ES in the KDC area should seek synergy between the construction of ecological security shied and industrial development based on the diversity, stability and sustainability of ecosystems; the path is to maximize the supply of ES based on the optimization of ecosystem functions, and at the same time to apply both governmental and market instruments to promote the transformation of the monetary value of grassland ES; the guarantee mechanisms are the engagement of stakeholders or right-holders, the improvement of governmental public management services, and the establishment of the economic system feedback system.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YL contributed to the conceptualization, data curation, formal analysis, investigation, methodology, and drawing. KX contributed to the writing—review and editing, funding acquisition, and supervision. SS contributed to the writing—review and editing and formal analysis. WZ contributed to the drawing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1240431/full#supplementary-material

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