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REVIEW ARTICLE

Ecology and sustainability of the Inner Mongolian Grassland: Looking back and moving forward

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Abstract
Context Understanding the ecology and sustainability of the Inner Mongolian Grassland is crucial for improving land management policies in the Mongolian Plateau and beyond. However, a systematic and comprehensive review of the relevant literature is still lacking.
Objectives This review was intended to: (1) assess the current state of the ecological and sustainability research of the Inner Mongolian Grassland region, and (2) identify critical research topics and challenges for understanding pathways to sustainability of the region.
Methods We conducted a bibliometric analysis of 2571 English articles indexed in the Web of Science during 1998–2019. Multiple methods, including descriptive statistics, principal component analysis, change point detection, theme mining, and association strength analysis, were combined to analyze the sampled literature.

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Results All reviewed studies can be grouped into four types: description of ecological and biogeochemical characteristics of degraded grasslands (type I), the impacts of climate change and human activities on aboveground (type II) and belowground grassland ecosystem functioning (type III), and the impacts of different management strategies on grassland ecosystem services and human well-being (type IV). The number of publications in all four themes has rapidly increased after 2007–2009. The four types of articles were related to each other in terms of the interannual publication consistency. Keyword co-occurrence network analysis showed that climate change and grazing were the major research topics, which are closely related to all other topics.
Conclusions Three perspectives have persisted in the ecology and sustainability research of the Inner Mongolian Grassland: Ecology in the Grassland, Ecology of the Grassland, and Sustainability of the Grassland. Based on the emerging landscape sustainability science framework, the transdisciplinary approach to landscape sustainability diagnostics and landscape planning and design should become a priority in advancing sustainability research of the region.

Keywords Inner Mongolian Grassland · Landscape sustainability science · Climate change · Grazing

Introduction

Drylands account for 40% of the world's terrestrial area and serve home to one-third of the world's population while maintaining multiple ecosystem services (Reynolds et al. 2007). Grasslands are the most widespread ecosystem type in drylands, which play an important role in sustaining animal husbandry and maintaining crucial ecosystem functions in arid and semi-arid regions (Suttie et al. 2005; Wu et al. 2015). The Eurasian grassland is the largest continuous grassland and one of the major animal husbandry production areas in the world (Suttie et al. 2005). As an important part of the Eurasian grassland, the Inner Mongolian Grassland occupies 866,700 km^2 and provides home for 25.34 million people as of 2018. Despite the relatively low population density in the Inner Mongolian Grassland, it has long played a key role in sustaining large groups of nomadic people and supporting their livelihood and culture, as well as traditional ecological knowledge, thus allowing to preserve environmental sustainability and continuous supply of renewable resources (Wu et al. 2015).

The Inner Mongolian Grassland is characterized by a temperate continental climate, with distinct east–west precipitation and temperature gradients. Dominant zonal ecosystems of the area include meadow steppe, typical steppe, and desert steppe. Non-zonal ecosystems (e.g., wetland and sandy land) are interspersed in this area reflecting changes in topography (Fig. 1) (Wu and Loucks 1992; Wu et al. 2015). The Inner Mongolian Grassland is home to 2781 species of plants (7.7% of Chinese plants), 467 species of birds (31% of Chinese birds), and 149 species of mammals (25.3% of Chinese mammals) (Feng et al. 2019). Such high regional biodiversity has produced important ecological services, including the provision of a total carbon sink of about 152 million tons, accounting for 17% of China's total carbon sink (Zhao 2015). Windbreaker tree planting and sand fixation are widely practiced here to allow the region to maintain its ecological integrity. The total area of amelioration here has reached 4.4 million km^2, or 46% of the China's total (Inner Mongolia-Ningxia Joint Inspection Group of Chinese Sciences of Academy 1985). As such, the Inner Mongolian Grassland is generally viewed as the important ecological frontier in Northern China. However, climate change, overgrazing, and mineral overexploitation (Ma et al. 2018; Wang et al. 2017) have all resulted in severe environmental degradation leading to biodiversity loss (Bai et al. 2007; Yan et al. 2020), productivity reduction (Zhang et al. 2017b), land degradation (Mao et al. 2018), ecosystem function decline (Shang et al. 2019), and increased poverty in pastoral areas (Li and Huntsinger 2011). Large-scale grassland degradation has been occurring since 1960s with about 90% of the area being affected by degradation (Li 1997; Wu et al. 2015).

Environmental issues in the Inner Mongolian Grassland have caused widespread concerns among the public and academics. Chinese scientists have embarked on extensive research on these issues (Jiang et al. 2006; Wu et al. 2015) with a particular focus on the assessment of biodiversity patterns (Zhang et al. 2016), community stability (Bai et al. 2004), soil characteristics (Zhao et al. 2007), lake disappearance

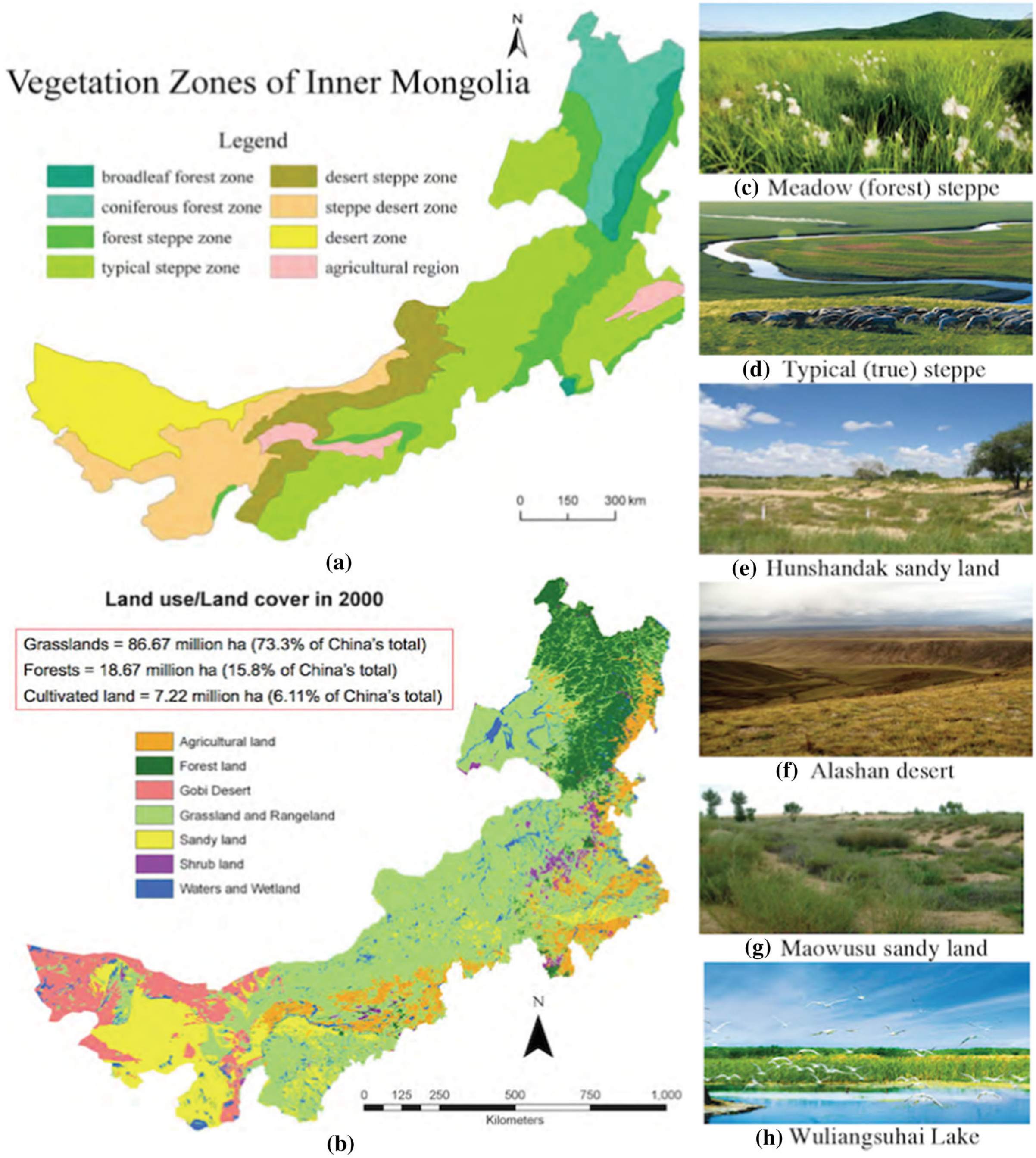

Fig. 1 Vegetation zones (**a**), land use and land cover in 2000 (**b**), and examples of dryland and wetland ecosystems (**c–h**) in Inner Mongolia, northern China (based on Wu et al. 2015)

(Tao et al. 2015), ecosystem services (Zhao et al. 2017), and human well-being (Yuan et al. 2015). Important summaries and analyses have also been conducted by international scholars and research teams (Schoenbach et al. 2009; Bryan et al. 2018). Most of these studies have focused on three major types of social-ecological systems in this region, including agricultural (Yin et al. 2012), pastoral (Li et al. 2018), and the agro-pastoral ecotone (Liu et al. 2018). The region has been studied at a variety of scales from the broad scale of the whole area (Bai et al. 2007) to the county (banner) level (Li et al. 2014) and the individual herdsman household level (Zhao et al. 2019). Heavy involvement of government in environmental restoration and mitigation is also noteworthy. In particular, since 2000 many ecological restoration programs have been launched by government agencies, including the Grain for Green Project (Jia et al. 2014), the Three North Shelter Forest Program (Ji et al. 2018), and Grassland Ecological Compensation Policy (Hu et al. 2019). Although some programs have caused adverse environmental outcomes, the overall effect is quite positive - many ecosystem functions have been restored and environmental degradation has slowed down (Bryan et al. 2018; Cao et al. 2019; Liu et al. 2020a).

Sustainability and sustainable development concepts emerged in response to such problems as biodiversity loss, ecosystem services reduction, environmental pollution, and global climate change (WCED 1987). Sustainability science was proposed as a scientific basis for sustainable development (Kates et al. 2001), and ever since has been developing rapidly (Bettencourt and Kaur 2011; Wu 2013; Fang et al. 2018). Wu (2013) argued that regional landscapes represent the most operational spatial scale domain for sustainability research and practice and proposed the landscape sustainability science framework, which promotes the integration between natural and social sciences, particularly, among landscape ecology, sustainability research, and landscape planning and design (Liao et al. 2020; Opdam et al. 2018; Wu 2019). With sustainability science emerging as a new paradigm relevant for many disciplines (Wu 2014), several studies have been carried out to better understand the ecology and sustainability of the Inner Mongolian Grassland (Wu et al. 2015; Chen et al. 2018). However, a systematic and comprehensive bibliometric-based review of those research problems is still lacking.

Therefore, applying a bibliometric analysis, here we explored the trends and research themes in ecological and sustainability-related studies published in the last two decades to answer the following two questions: (1) What is the current state of the art of ecological and sustainability research of the region? (2) What are critical research topics and challenges that need to be addressed to promote the sustainability of the region?

Methods

Literature search

Bibliometrix is the comprehensive bibliometric analysis package based on R programming language. It conveniently assists in performing literature collection, analysis and visualizations (Aria and Cuccurullo 2017), and became a useful tool for revealing the development of concepts and trends in a scientific field (Vargas et al. 2019; Zhou et al. 2019). Bibliometrix currently supports literature search from four databases: Clarivate Analytics Web of Science (WoS), SCOPUS, Cochrane Database of Systematic Reviews, and PubMed. Considering that the WoS Core Collection is widely recognized and cited in the academic world, we conducted the literature analysis by searching for such words as '*grassland*' or '*grasslands*', '*steppe*' or '*steppes*', '*rangeland*' or '*rangelands*', 'and', '*Inner Mongolia*' or '*Inner Mongolian*' in titles, abstracts, or keywords of English WoS papers published before December 31, 2019. The total number of articles obtained was 2571.

Descriptive analysis

Co-word analysis is one kind of a technique to build the science map, which displays structural and dynamic aspects of scientific research (Callon et al. 1983). Keywords (authors' keywords, journals' keywords, etc.) are most commonly selected for the co-word analysis (Cobo et al. 2011), but it is not limited to those. The analysis is capable of extracting phrases from titles, abstracts and keywords as well (Zhou et al. 2019). Considering these capabilities and based on the premise that keywords proposed by the authors reflect explicitly their views of the research problem and structure of those studies (Zhou et al. 2019), we conducted a series of analyses of 2571 articles by focusing on authors' keywords.

Principal component analysis (PCA) is a powerful method of reducing data dimensions and providing an overview of complex multivariate data. It can be used to visualize the clustering of samples and reveal relations between them. A scatter plot is more readily seen if there are certain groupings between samples. Samples that are close in this transformed dimensions are similar (Bro and Smilde 2014). We first performed a PCA on 2571 papers based on keywords and clustered them into four types. Then, we obtained the following descriptive statistics for all articles and for each type of article individually: number of papers, number of journals, the average citations per paper, the number of authors, the top ten most productive institutions, the top ten journals in terms of the number of publications, and the collaboration index. Collaboration index is calculated as the total number of authors of multi-authored articles divided by the total number of multi-authored articles. PCA analysis was completed using the *vegan* package in R programming language.

Trend and change point detection

Based on the number of papers published each year, the Mann–Kendall test was used to determine trends for all papers and for each individual type of paper (Fang et al. 2018). Pettitt's test method was further applied to find potential change points in those trends (Pettitt 1979). Both tests were performed using the *trend* package in R programming language.

Theme mining

To determine the structure and evolution of research themes in each type of papers, we drew the conceptual structure and produced thematic maps based on the analysis of keywords. The conceptual structure map showed the clustering and linkages of research themes of each type of papers. The thematic evolution map is based on the keywords and builds the evolutionary relationship of themes through two measurement indicators: Callon's centrality and Collon's density (Cobo et al. 2011). The horizontal axis is the Callon's centrality, which represents the degree of connection between a certain theme and other themes. It can be interpreted as the importance of this theme in the entire field development. The vertical axis is the Collon's density, which represents the degree of connection within a certain theme. It can be interpreted as the development status of the theme. Both the conceptual structure and thematic maps were drawn using the *bibliometrix* package in R programming language.

Association strength analysis

To determine the correlation among types of papers, Spearman's correlation analysis of the number of annual publications of each type of paper was first used (Zhou et al. 2019). Then, the Sørensen similarity coefficient based on keywords between every two types of papers was calculated:

$$S_{sim} = \frac{2a}{2a + b + c}$$

where a refers to the number of co-occurrence keywords in both types of papers, b and c represent the number of keywords that appear only in each type. High values of Sørensen coefficient correspond to high similarity (Sørensen 1948). Furthermore, we recorded the co-occurrence of keywords of four types of papers and constructed a word cloud. Co-word network analysis was used to reveal the network graph of these co-occurrence keywords from 2571 papers. Spearman's correlation analysis and Sørensen similarity coefficient were performed using the *vegan* package in R programming language. A word cloud was drawn using the *wordcloud* 2 package in R programming language. Network analysis was conducted using the *bibliometrix* package in R programming language.

Results

Descriptive statistics for all articles

Among the 2571 articles, 60 were single-author and 2511 were multi-author articles (Table 1). The number of annual publications showed an exponential growth pattern during 1998–2019, with an annual growth rate of 20.83%. The year of 2008 was a change point, the number of articles increased significantly after that year (Table 1, Fig. 2a). All articles were cited on an average of 17.52 times. Article citations also showed an exponential increase with an acceleration since 2008 (Table 1, Fig. 2b). The articles came from 523 journals, with *Plant and Soil* being the most published journal (89 articles), followed by the *Journal of Arid Environment* (79 articles), and *PLOS One* (75 articles) (Table 1, Fig. 2c). There was a total of 4807 authors with an average of 1.86 authors per article and the collaboration index of 1.89. Most of the top ten

Table 1 Basic statistics for all articles and the four types of articles

	Type I	Type II	Type III	Type IV	All
Number of articles	172	2227	136	36	2571
Annual percentage growth rate	11.57	20.38	12.88	5.08	20.83
Number of journals	104	491	80	31	523
Average documents per journal	1.65	4.54	1.7	1.16	4.92
Number of authors	626	4470	528	155	4807
Average citations per article	20.69	16.73	25.74	20.08	17.52
Average authors per article	3.64	2.01	3.88	4.31	1.87
Authors of single authored articles	7	43	4	0	52
Authors of multi authored articles	619	4427	524	155	4755
Single-authored articles	7	49	4	0	60
Multi-authored articles	165	2178	132	36	2511
Collaboration Index	3.75	2.03	3.97	4.31	1.89

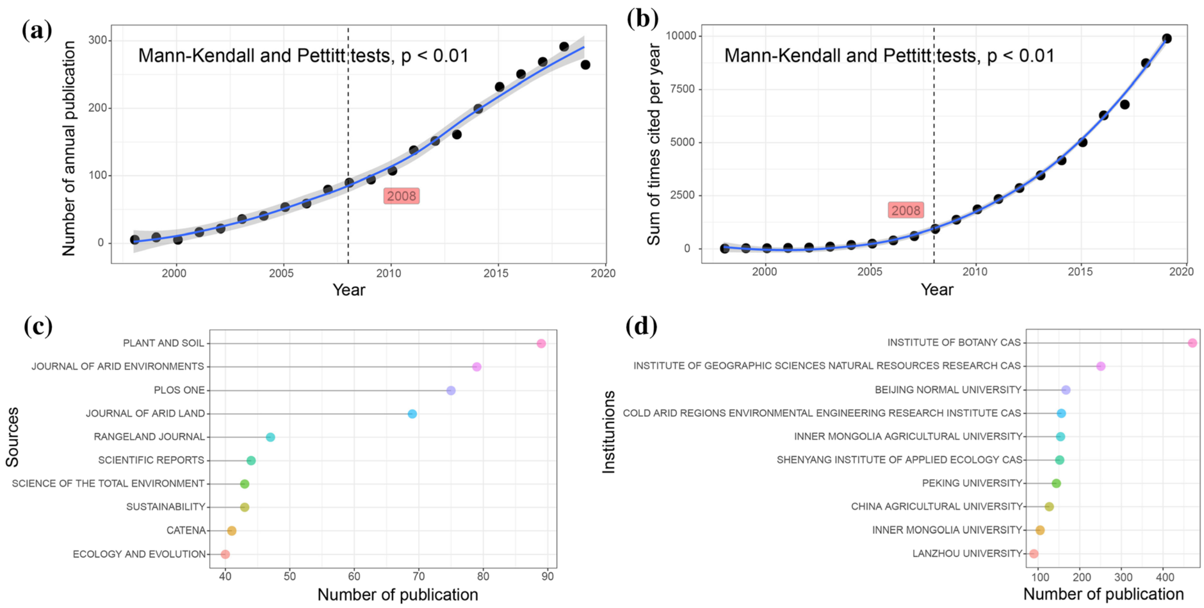

Fig. 2 Descriptive statistics for all articles. **a** Temporal trend and change point of all papers in terms of annual publications; **b** Temporal trend and change point of all papers in terms of sum of times cited per year; **c** Top ten journals in terms of the number of publications; **d** Top ten institutes in terms of the number of publications

institutions came from the Chinese Academy of Sciences (CAS), with the Institute of Botany CAS, the Institute of Geography Sciences and Natural Resources Research CAS, and Beijing Normal University being the top three (Fig. 2d).

Descriptive statistics of the four types of articles

PCA analysis of keywords clustered all articles into four types (Fig. 3). The number of articles and the annual growth rate between the types were different. The number of type II articles was the highest (2227). The type had also the highest annual growth rate (20.38%). There were only 36 of type IV articles; they showed the lowest annual growth rate (5.08%) (Table 1). Type I and II exhibited the change point of publication trajectory in 2008, while type III change point was in 2009 and type IV change point was in 2007 (Fig. 4).

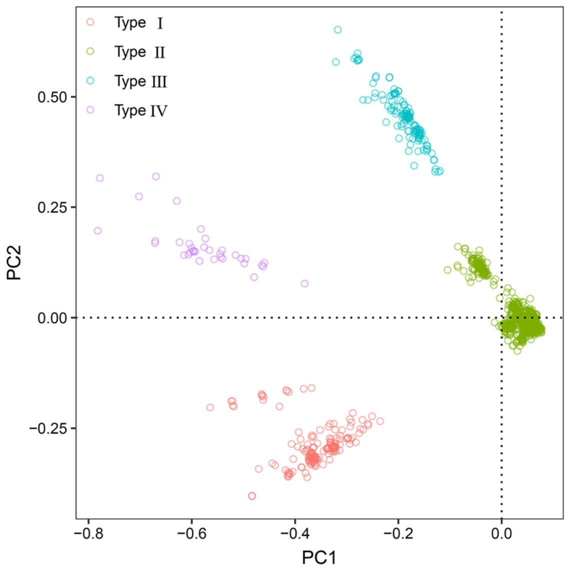

Fig. 3 Four clusters of research types identified by PCA

Major differences were found in journals publishing these four types of articles (Fig. 5). Type I articles were published in 104 journals with most appearing in *Journal of Arid Land*. Type II articles were published in 491 journals, most articles published by *Plant and Soil*. Type III articles were published in 80 journals, with most appearing in *Agriculture Ecosystems & Environment*, *Journal of Soils and Sediments*, and *Plant and soil*. Type IV articles were published in a wider range of 31 journals with an average of 1.16 articles per journal. With an average of 4.54 articles per journal type II articles tended to be most focused on each journal's scope (Table 1).

Average number of authors per article was quite different between the types. Type II articles had the lowest (only 2) and type IV articles had the highest (4.31) average number of authors (Table 1). In terms of article citations, type II articles had the lowest

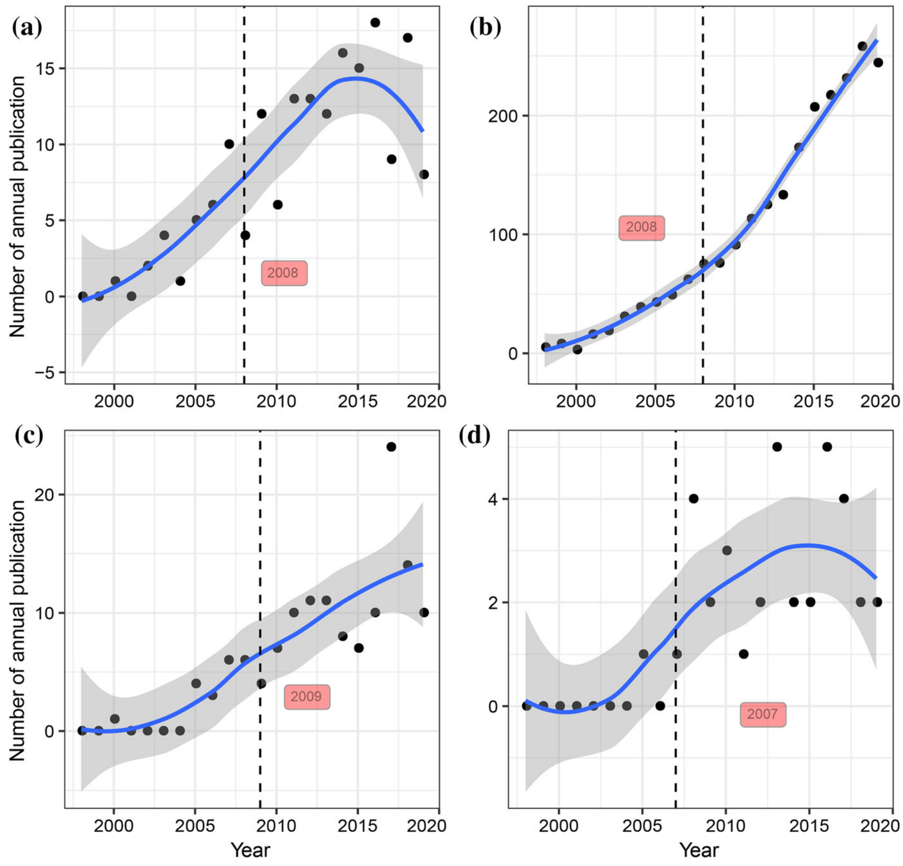

Fig. 4 Temporal trends and change points of four types of articles based on Mann–Kendall and Pettitt's tests. All tests are significant at $p < 0.01$. Type I (**a**), type II (**b**), type III (**c**) and type IV (**d**)

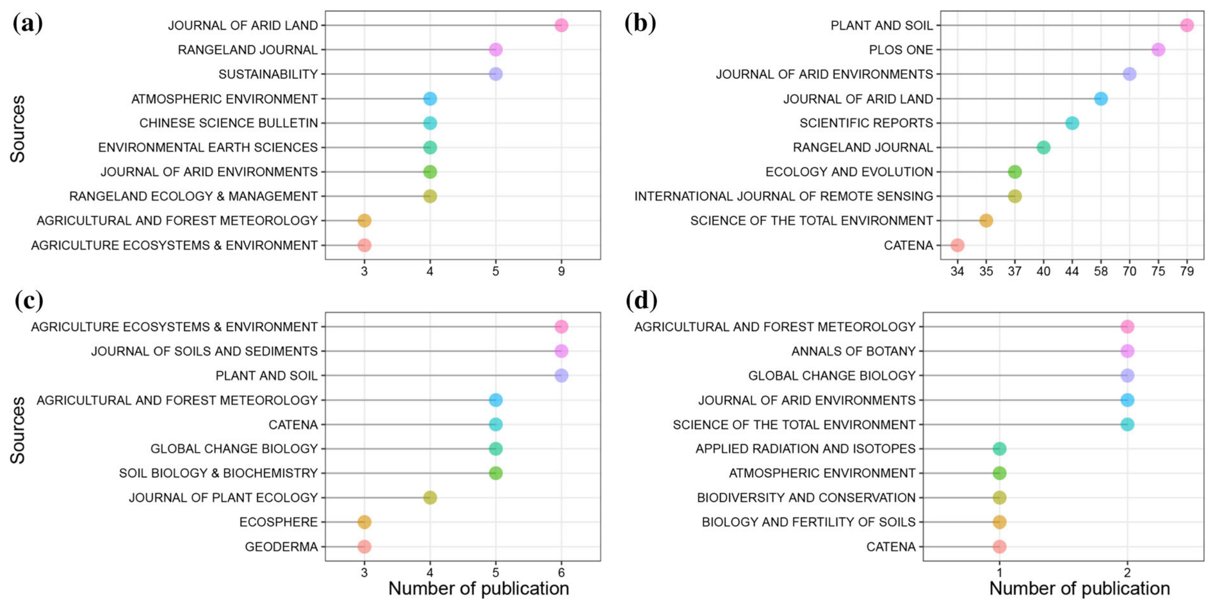

Fig. 5 Top ten journals publishing articles of four types, type I (**a**), type II (**b**), type III (**c**), type IV (**d**)

citation rate (an average of 16.73 times cited per article), and type III articles had the highest citation rate (25.74 times cited per article) (Table 1).

Theme mining

Thematic composition derived from keywords was quite different for different types of articles (Fig. 6). Type I articles mainly involved two themes. The first theme was centered on plant community structure, species diversity, and soil wind erosion in the context of grassland degradation. The second theme focused on the differences in precipitation, temperature, soil, and vegetation in meadow steppe, typical steppe, and desert steppe. Type II articles had three themes. The first focused on impacts of climate change and human activities (e.g., grazing, land use, etc.) on grassland community diversity, community structure, and ecosystem function in aboveground vegetation. The second theme discussed the relationship between community composition and ecological stoichiometry. The third theme was closely related to greenhouse gas emissions, such as carbon dioxide, nitrous oxide, and methane. Type III articles also had three main themes. The first was mainly centered on impacts of climate change and human activities on soil characteristics, soil organic carbon content, and microbial diversity in underground ecosystems. The second focused on impacts of land use on soil organic carbon and nitrogen in the agro-pastoral ecotone. The third was centered on the spatial pattern of soil and vegetation under overgrazing. Likewise, type IV articles had three themes. The first focused on the response of grassland communities, soil microorganisms, ecosystem services, and human well-being to adaptive management. The second analyzed the regulation of ecosystems by grazing management through a negative feedback mechanism. The third theme discussed functional traits (e.g., leaf life, and leaf N content) under the coupling of water and fertilizer.

The thematic map revealed the evolution of themes by classifying them into four quadrants, in which density and centrality are plotted in a two-dimensional diagram (Fig. 7). Themes in the first quadrant developed well and were closely related to other themes. These themes, termed motor-themes, included grazing, species diversity, nitrogen deposition, productivity, plant communities, and ecological stoichiometry. Themes in the second quadrant were often well developed but not closely related to other themes. These themes, termed very specialized themes, included land use and management, ecosystem functions and services, ecosystem restoration and environmental sustainability, policies, and pasture management. Themes in the third quadrant developed

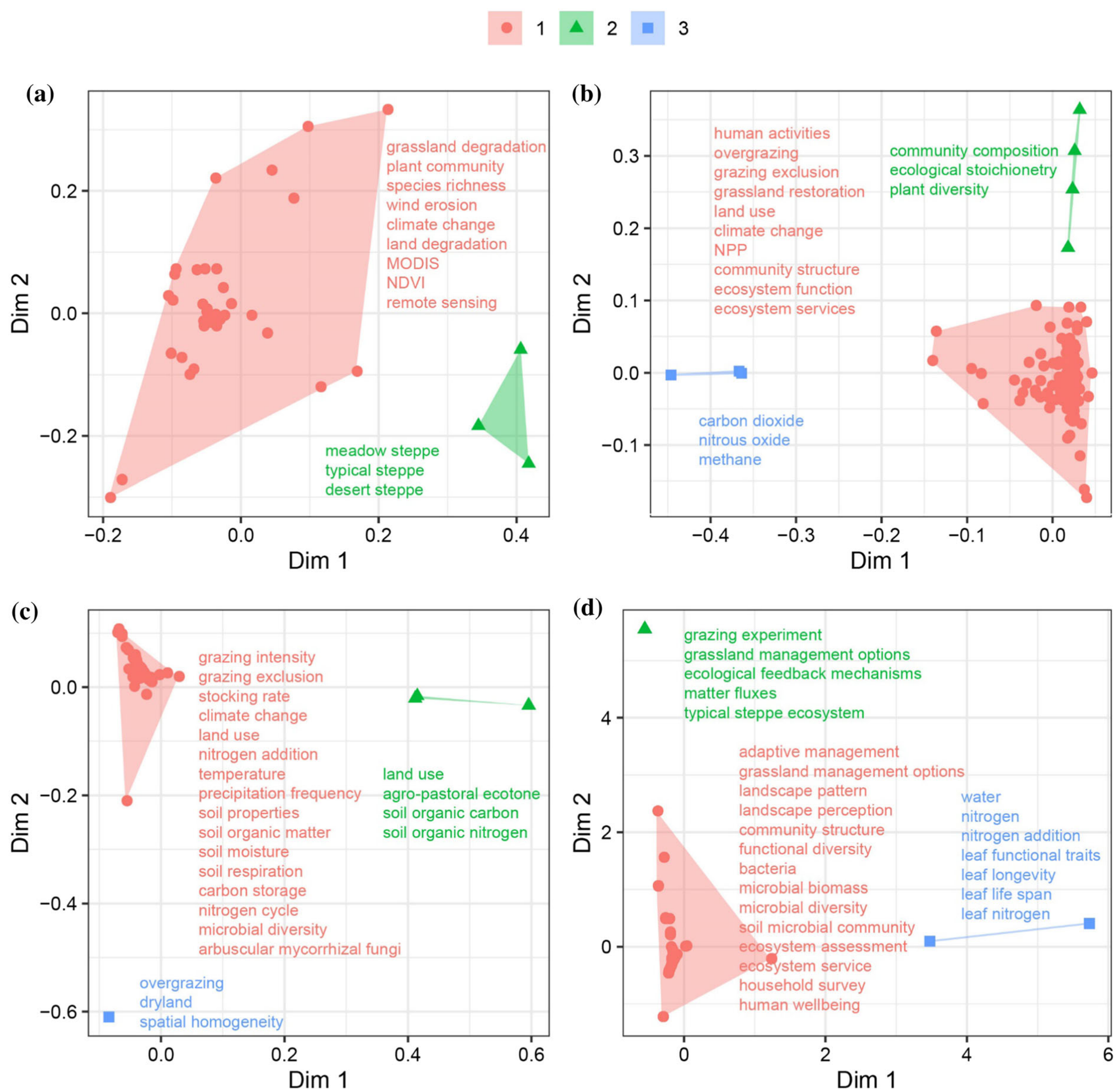

Fig. 6 Cluster analysis of research themes in four types of articles, type I (**a**), type II (**b**), type III (**c**), type IV (**d**). Orange, green, and blue represent first, second, and third themes in each type of articles, respectively. Circles, triangles, and squares represent keywords of first, second, and third themes

weakly and were very isolated. These themes were termed emerging or disappearing themes and included warming, nutrition, precipitation, drought, phosphorus and community construction. Themes in the fourth quadrant developed weakly but were closely related to other themes. These themes were termed basic themes and included desertification, grassland degradation, soil organic carbon, overgrazing, and plant functional groups.

Relationships between the four types of articles

The relationship between the annual publication rate of different types of articles can reflect their consistency (Zhou et al. 2019). The Spearman's correlation analysis revealed consistency among the four types of articles (Fig. 8a). Sørensen similarity coefficients were all higher than 0.10, except for the similarity between types II and IV (0.03), indicating that they

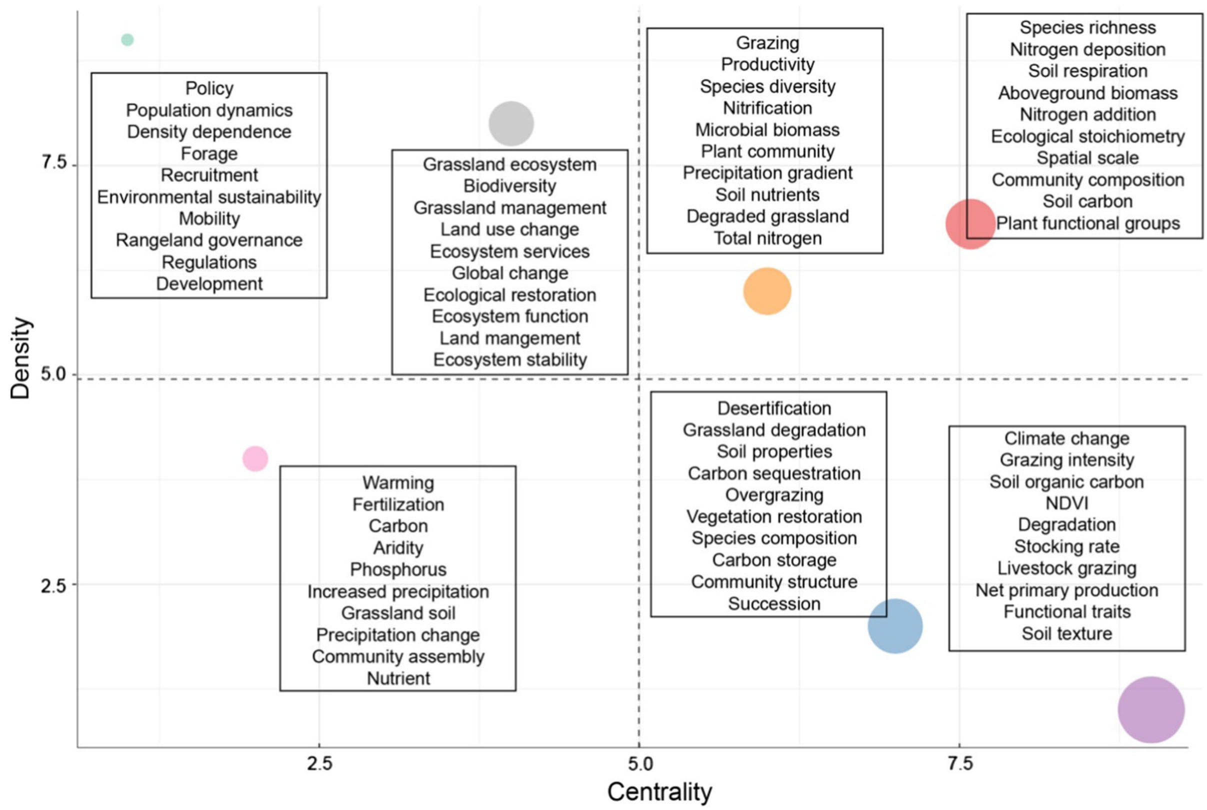

Fig. 7 Thematic evolution map based on keywords. The thematic evolution map builds the evolutionary relationship of themes based on two indicators: the connection degree between themes (centrality) and within a certain theme (density). The solid circle represents a document containing a series of keywords. The area of the solid circle is proportional to the total number of keywords corresponding to each document. The abscissa and ordinate numbers are rank values based on the median

were closely related (Fig. 8b). Fifteen co-occurrence keywords were found among the four types of articles (Fig. 8c). Climate change, grazing, and grazing intensity were the keywords with the highest occurrence. They were also closely related to other keywords (Fig. 8c, d).

Discussion

Three perspectives in the ecology and sustainability of the Inner Mongolian Grassland

Due to differences in concepts, research approaches, and scales, different perspectives may be often formed in the same research field (Ramanathan and Feng 2009; Wu 2014). Wu (2014) summarized three perspectives developed in the field of urban ecology: the "ecology in cities", "ecology of cities", and "sustainability of cities". Analogous to these, we propose that research on ecology and sustainability of the Inner Mongolian Grassland can also be viewed through the lenses of such perspectives: "Ecology in the Grassland", "Ecology of the Grassland", and "Sustainability of the Grassland". The "Ecology in the Grassland" perspective regards grassland as a habitat of soil-grassland system. It is consistent with the research themes of type I, which focus on plant community structure, diversity, and soil erosion. Therefore, we can relate type I research theme to the "Ecology in the Grassland" perspective. The "Ecology of the Grassland" perspective regards grassland as a natural ecosystem of soil-grassland-animal system. It is closely related to the research themes of type II and III, which are centered on effects of grazing and

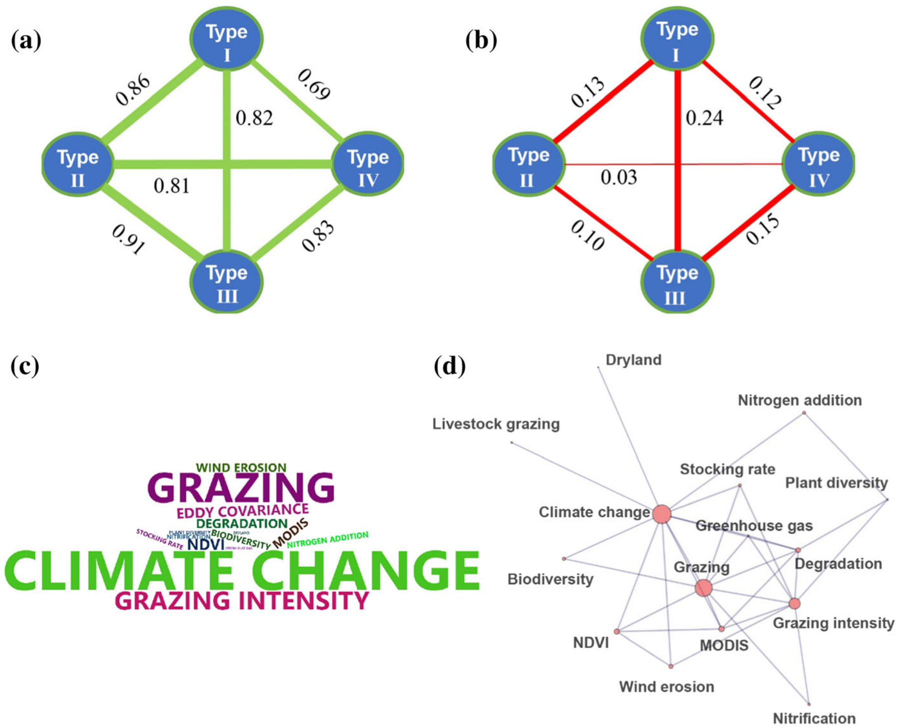

Fig. 8 Theme association analysis. **a** Spearman's correlation analysis based on the annual publication of four types of articles; **b** Sørensen similarity coefficients of four types of articles; **c** Word cloud of co-occurrence keywords among the four types of articles; **d** Network analysis of co-occurrence keywords among the four types of articles

climate change on aboveground and underground parts of grassland ecosystems, respectively. As such, types II and III research themes fit into the "Ecology of the Grassland" perspective. The "Sustainability of the Grassland" perspective regards grassland as a soil-grassland-animal-human social-ecological system. It fits the research themes of type IV, which mainly explore ecosystem services and human well-being with adaptive management. Therefore, type IV research theme can be identified as the "Sustainability of the Grassland". Unlike the three perspectives of urban ecology, which reflect the historical evolution of the field and the influence of different schools of thought (Wu 2014), the three perspectives in the ecology and sustainability of the Inner Mongolian Grassland were practiced over a shorter period of time and arose almost simultaneously (Fig. 4). Compared to urban ecology, which has developed over about a hundred years in different parts of the world, most notably Europe, North America, and Australia (Wu 2014), the grassland research specific to the Inner Mongolian Plateau is more focused and has mostly flourished in the past two decades (Fig. 2a). Differences in those three perspectives of the Inner Mongolian Grassland research can be analyzed with respect to several key aspects (Fig. 9).

The "Ecology in the Grassland" perspective treats grassland as "habitat". "Soil" and "grass" are often deemed as isolated research objects in those studies. Plant community structure, species diversity, soil wind erosion, and soil physical and chemical properties are the typical themes in this traditional perspective in grassland research. Yet, some studies have also looked at human and nature interactions and analyzed human activities (Fig. 6a). The focus of this perspective is on community ecology, which is usually analyzed by conducting surveys and regional censuses following the methods and theory of community ecology (Bai et al. 2004; Zhao et al. 2007). When the perspective is viewed in terms of the three pillars of sustainability—environmental integrity, social equity, and economic viability (Wu 2013)—it does only emphasize the environmental integrity and lacks a comprehensive view of sustainability.

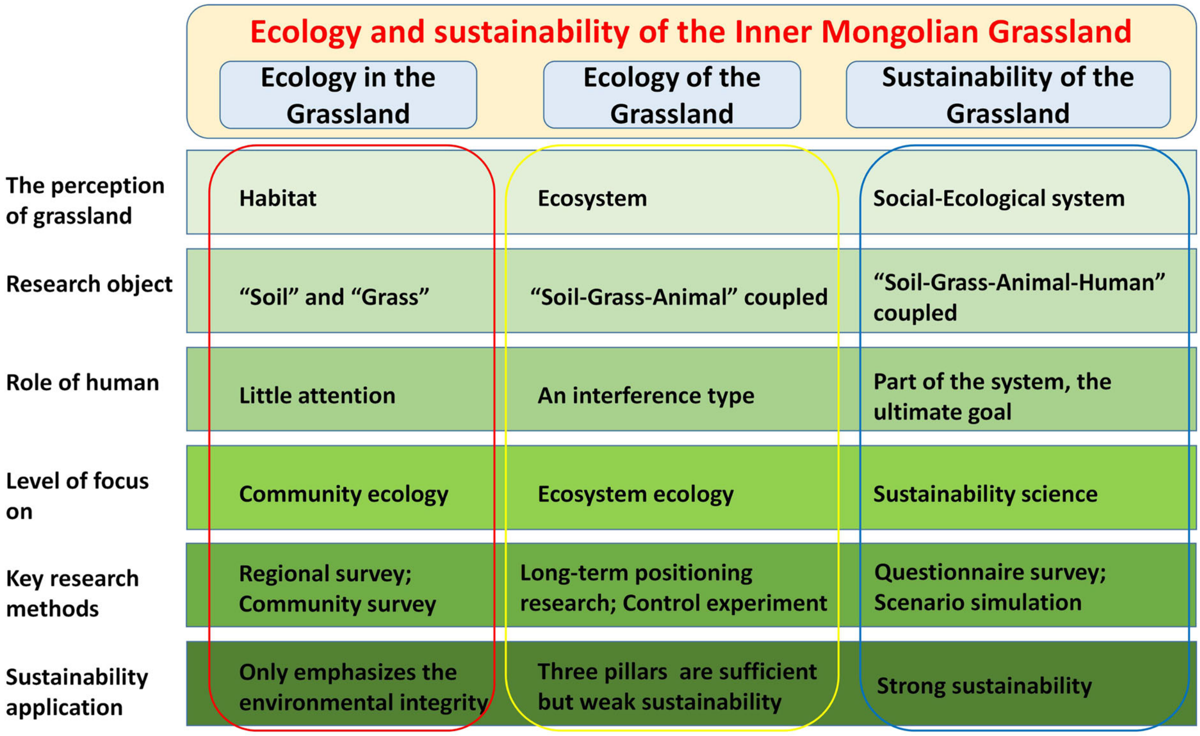

Fig. 9 Characteristics of the three perspectives in ecology and sustainability of the Inner Mongolian Grassland

The "Ecology of the Grassland" perspective focuses on grassland ecosystems and highlights the "soil-grass-animal" systems (Ren et al. 2016). This perspective emphasizes the relationship between vegetation and soil, as well as impacts of human activities, especially grazing and anthropogenic climate change, on grasslands. Research here mainly focuses on aboveground components (e.g., grassland community diversity, ecosystem functions and services) (Fig. 6b) and below ground components of ecosystems (e.g., soil characteristics, soil organic, carbon content, and microbial diversity) (Fig. 6c). In this perspective, humans in these systems are viewed as a type of disturbance (Robinson et al. 2017; Liu et al. 2020a). Such studies draw from the theory of ecosystem ecology and widely employ such research approaches as long-term observations and experimentation (Guo et al. 2016). The perspective involves all three pillars of sustainability—-environmental integrity, social equity, and economic viability. For the sake of survival and development, human society exploits resources made available by grasslands, which leads to the degradation of grassland ecosystems. This imbalance between human activities and grassland ecosystems is defined as weak sustainability, which postulates that, if needed, the natural capital can be easily substituted (Wu 2013; Fang et al. 2018).

The "Sustainability of the Grassland" perspective combines social-ecological systems with grassland ecosystems and emphasizes the more inclusive "soil-grass-animal-human" systems (Ren et al. 2016). Grasslands provide a variety of ecosystem services for the human society (Zhao et al. 2020). People, as part of the social-ecological system, not only affect the grasslands in the form of disturbances but also achieve their goal of improving human well-being through adaptive management (Fig. 6d). Sustainability is the focus of this perspective. Social-ecological systems are studied with a variety of methods including both traditional ecological methods of research and questionnaires surveys, computer simulations, and scenario evaluations (Zhao et al. 2019). Unlike the "Ecology of the Grassland", this perspective emphasizes not only human well-being but also the maintenance of ecosystem services. Most now realize that economic growth is highly dependent on natural capital, such as land resources, but pursuing only the economic value of natural capital would be incorrect.

Human capital and natural capital cannot be fully substituted, and any development can only endure if it is based on sustainability principles. This perspective follows the idea of strong sustainability (Wu 2013; Fang et al. 2018).

Although the three perspectives were discussed separately, they are not isolated but instead are closely related to each other (Fig. 8) and can be arranged hierarchically to elucidate the sustainability of the Inner Mongolian Grassland (Fig. 10). Complexity of systems being the focus of each perspective tends to increase with levels of this nested hierarchy. Those systems change from soil-grass to soil-grass-animal and soil-grass-animal-human, respectively. What also increase are the degrees of transdisciplinarity and the emphasis on human wellbeing up the levels of hierarchy. The "Ecology in the Grassland" perspective emphasizes multidisciplinary research with relatively loose connections between disciplines. The interdisciplinary emphasis of the "Ecology of the Grassland" perspective unites multiple disciplines by pursuing a clearly defined common goal. The "Sustainability of the Grassland" perspective emphasizes transdisciplinary research, which, in addition to close interactions of multiple disciplines and the common research goal, is characterized by the involvement of not only academics, but also non-academic stakeholders and government agencies (Wu 2006). The "Ecology in the Grassland" perspective is largely committed to explaining the "pattern", that is, grassland community and soil characteristics, which is more conducive to the diagnosis of grassland degradation. The "Ecology of the Grassland" focuses on the "impact", that is, the effects of climate change and human activities on the grassland ecosystem, which is instrumental for the restoration of degraded

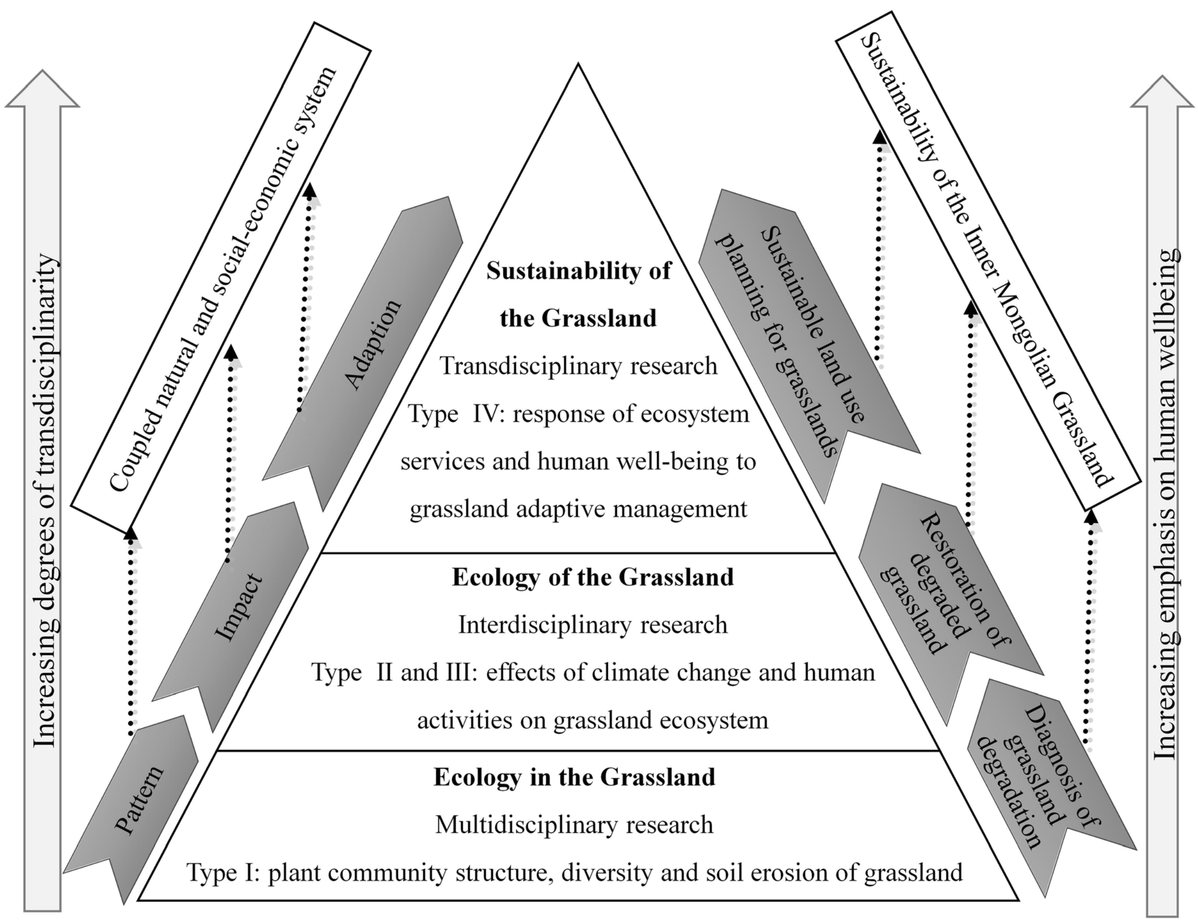

Fig. 10 A hierarchical perspective on the relationship among the three research perspectives, as well as the four research themes (based on Wu 2006)

grasslands. The "Sustainability of the Grassland" addresses the "adaptation", or mitigation of adverse effects and improvement of ecosystem services and human well-being with the overall goal of developing strategies for sustainable grassland spatial design and planning on a regional scale. The three perspectives are linked together in the pursuit of multi-level research of coupled natural and social-economic systems. The ultimate goal is the sustainability of the Inner Mongolian Grasslands.

Future research topics for the ecology and sustainability of the Inner Mongolian Grassland

Our analysis revealed ample evidence of research conducted to understand the ecology and sustainability of the Inner Mongolian Grassland. Those studies can be further grouped into the three perspectives, for which we would now like to identify key research priorities. The "Ecology in the Grassland" perspective focuses on the changes in soil and plants in the grassland (Fig. 6a). One main theme that emerged in this perspective is centered on biodiversity patterns. While many biodiversity studies are focused on broad scales of the entire area (Zhang et al. 2014), research projects analyzing biodiversity patterns at the community level and finer scales are relatively rare (Jones et al. 2019). However, understanding community assembly mechanisms based on functional traits is useful for revealing the formation and maintenance of diversity at the community scale (Kattge et al. 2020). Studies of community assembly, as an emerging theme, are relatively lacking in the Inner Mongolian Grassland (Fig. 7). Intraspecific variation of functional traits, which has important effects on community assembly, also requires further research (Anderegg et al. 2018). Thus, future studies should attempt to explain the impacts and maintenance mechanisms of intraspecific variation on community assembly based on functional traits. On the other hand, previous studies mainly focused on biogeochemistry, including soil water content, soil carbon and soil nitrogen content, and soil phosphorus (Bai et al. 2008, 2010). Soil phosphorus has become an emerging theme in the Inner Mongolian Grassland (Fig. 7). In recent years, soil phosphorus was found to affect soil microorganisms, the interspecific interactions and plant community composition, and it eventually plays an essential role in regulating interactions between above- and belowground components of ecosystems (Guo et al. 2016; Chen et al. 2019). Therefore, soil phosphorus should be become a research priority of future studies.

The "Ecology of the Grassland" perspective emphasizes the coupled "soil-grass-animal" system (Fig. 6b, c). Biodiversity and ecosystem function relationships have been an important research problem in ecology (Fig. 7). Future studies in this direction are expected to focus on two issues. First, with most previous studies being limited to the relationship between aboveground plant diversity and a single ecosystem function of interest (Bai et al. 2007; Zhang et al. 2017a), future projects should focus on simultaneous analysis of aboveground and belowground components of ecosystems. This will help in revealing adaptation mechanisms of biodiversity and multiple ecosystem functions to global changes and human impacts at different trophic levels (e.g., plants, soil animals, and soil microorganisms) (Wang et al. 2019, 2020). Second, interaction mechanisms between the above- and belowground ecosystem components should receive close attention. Specifically, we need to learn how aboveground parts (herbivores and plants) regulate the belowground ones (soil animals and microorganisms), and understand top-down flows and bottom-up feedbacks (Yang et al. 2014; Ye et al. 2018). We should also recognize the urgent need for multi-scale studies, which could help in deriving scaling relations between fine-scale controlled experiments and regional scale field surveys (Yuan et al. 2015).

The "Sustainability of the Grassland" perspective has emerged very recently. Therefore, only a limited number of studies focus on ecosystem services and human well-being (Figs. 4d, 6d), but these two themes have high potential for development in the future (Fig. 7). We identify four topics that should advance our understanding of sustainability in the area. First, the evaluation of ecosystem services should expand to all parts of the Inner Mongolian Grassland. The region as a whole offers unique ecosystem services for Mongolians allowing them to preserve and maintain their lifestyles and nomadic culture, while more studies are needed to fully evaluate cultural services of grassland landscapes (Chen et al. 2018; Shang et al. 2019). There are critical needs for developing a more unified system of indicators and methods of assessment in order to enhance comparability of studies and integration of assessments of different grassland regions (Bennett et al. 2015). Second, to examine the relationship between ecosystem services and human well-being we need to develop a better understanding of human well-being in this grassland area. A unified evaluation system is yet to be available to researchers (King et al. 2014). The other important problem in understanding those relationships is that they may be nonlinear at multiple levels and scales (Jordan et al. 2010; Wu 2013). In recent years, the cascading framework of "biodiversity—ecosystem function—ecosystem services—human well-being" has received widespread attention due to its promise to elucidate the formation of ecosystem services and their effects on human well-being (Wu 2013; Bennett et al. 2015). Third, sustainably minded land planning and design based on grassland ecosystem services is needed. The purpose of land planning and design is to improve human well-being. However, a difficult question yet to be answered is how to balance various factors within a specific region and implement optimal planning and design (Wu 2013, 2019). Research and engineering related to land planning and land management in the Inner Mongolian Grassland are scarce and need to be strengthened (Dong et al. 2017; Wang et al. 2017). Fourth, the recognition of different livelihood strategies in the area requires adaptive approaches to sustainability. Over history the Inner Mongolian Grassland has experienced nomadism, semi-sedentary, and full sedentary grassland management practices (Wu et al. 2015). With the implementation of the 'Double Power and One System Policy' different livelihood strategies have been formed in the Inner Mongolian Grassland (Robinson et al. 2017; Zhang et al. 2019). Those have been studied by analyzing the income, household characteristics, and livestock structure (Jiang et al. 2019; Liu et al. 2020b), but such issues as poverty and education have been overlooked. The critical research task is to assess the most successful livelihood strategy to meet the goal of achieving regional sustainability.

Coal mining, grassland reclamation, and urban expansion have modified grassland landscape patterns in many ways (Wu et al. 2015). Most notable changes occurred in the past decade, especially the fast spread of fencing and roads, which have further exacerbated grassland health (Deng et al. 2011). Recent studies have proposed measures for improving regional sustainability by optimizing grassland management (Kemp et al. 2013, 2018). In our view such efforts should benefit greatly from bringing the landscape ecological perspective since landscape scale is the most appropriate for addressing sustainability problems (Opdam et al. 2018; Wu 2019). Furthermore, we believe that adopting the recently proposed landscape sustainability science can help in combining the three perspectives and building a transdisciplinary research agenda for understanding the sustainability of these social-ecological systems (Fig. 11). The ultimate goal of landscape sustainability research in the Inner Mongolian Grassland is to optimize landscape patterns and improve ecosystem services and human well-being in the region. The framework can be used to couple the "soil-grass-animal-human" systems and study them as social-ecological systems from a strong sustainability perspective. This framework emphasizes the impacts of climate change, grazing, and other socio-economic factors on landscape patterns. Moreover, it integrates biodiversity and ecosystem processes to further explore the interrelationships among landscape patterns, biodiversity, ecosystem services, and human well-being. Finally, it is useful to optimize land planning and further enhance regional sustainability. Although the Inner Mongolian Grassland can be viewed as relatively homogeneous on a broad scale, we argue that landscape heterogeneity is abundant when viewed across multiples scales and spatial extents. Studies have found heterogeneity in topography, precipitation, soils, vegetation, as well as spatially and temporally variable utilization of landscapes across different scales, from household level to county or even to the entire region (Zhou et al. 2008; Wu et al. 2015; Zhang et al. 2019). Such heterogeneity should be considered in future research of sustainability of the Inner Mongolian Grassland.

Conclusions

We employed bibliometric analysis and reviewed research themes important for achieving sustainability goals in the Inner Mongolian Grassland. Although interest in adopting principles of regional sustainability of the area has gradually increased, it accelerated only after 2007–2009. The four types of previous studies identified included characteristics of degraded grasslands, the impacts of climate change and human

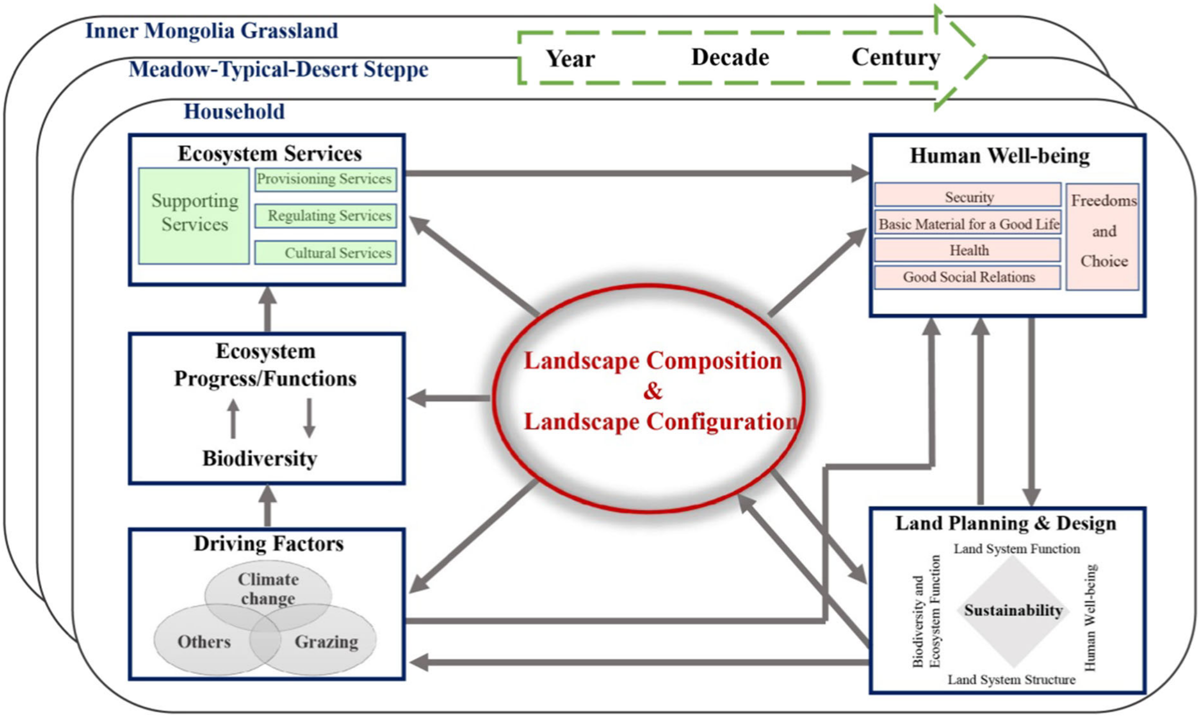

Fig. 11 Framework for sustainability research of the Inner Mongolian Grassland based on landscape sustainability science (based on Wu 2013)

activities on the aboveground and belowground components of grassland ecosystems, and the management of ecosystem services and human well-being. These studies are mainly based on three perspectives: "Ecology in the Grassland", "Ecology of the Grassland", and "Sustainability of the Grassland". The first perspective focuses on changes in grassland ecosystem characteristics. The second is centered on impacts of climate change and human activities on grassland ecosystems. The third perspective, which combines ideas of ecosystem services and human well-being, is crucial for advancing sustainability of the region, but it has received little attention until very recently. The bias in current research priorities indicates a gap between our knowledge and the changing landscape, especially in studies related to landscape planning and design. In the future, research based on principles and the framework of landscape sustainability science should become a priority. Doing so, we can eliminate narrow views of individual disciplinary perspectives, understand the functioning of grassland socio-ecological systems across scales, and identify pathways toward sustainability of the Inner Mongolian Grassland.

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References

Anderegg LDL, Berner LT, Badgley G, Sethi ML, Law BE, HilleRisLambers J (2018) Within-species patterns challenge our understanding of the leaf economics spectrum. Ecol Lett 21:734–744

Aria M, Cuccurullo C (2017) bibliometrix: An R-tool for comprehensive science mapping analysis. J Informetr 11:959–975

Bai Y, Han X, Wu J, Chen Z, Li L (2004) Ecosystem stability and compensatory effects in the Inner Mongolia grassland. Nature 431:181–184

Bai Y, Wu J, Clark CM, Naeem S, Pan Q, Huang J, Zhang L, Han X (2010) Tradeoffs and thresholds in the effects of nitrogen addition on biodiversity and ecosystem functioning: evidence from inner Mongolia Grasslands. Glob Change Biol 16:358–372

Bai Y, Wu J, Pan Q, Huang J, Wang Q, Li F, Buyantuyev A, Han X (2007) Positive linear relationship between productivity and diversity: evidence from the Eurasian Steppe. J Appl Ecol 44:1023–1034

Bai Y, Wu J, Xing Q, Pan Q, Huang J, Yang D, Han X (2008) Primary production and rain use efficiency across a precipitation gradient on the Mongolia plateau. Ecology 89:2140–2153

Bennett EM, Cramer W, Begossi A, Cundill G, Diaz S, Egoh BN, Geijzendorffer IR, Krug CB, Lavorel S, Lazos E, Lebel L, Martin-Lopez B, Meyfroidt P, Mooney HA, Nel JL, Pascual U, Payet K, Harguindeguy NP, Peterson GD, Prieur-Richard AHN, Reyers B, Roebeling P, Seppelt R, Solan M, Tschakert P, Tscharntke T, Turner BL, Verburg PH, Viglizzo EF, White PCL, Woodward G (2015) Linking biodiversity, ecosystem services, and human well-being: three challenges for designing research for sustainability. Curr Opin Environ Sustain 14:76–85

Bettencourt LMA, Kaur J (2011) Evolution and structure of sustainability science. Proc Natl Acad Sci USA 108:19540–19545

Bro R, Smilde AK (2014) Principal component analysis. Anal Methods 6:2812–2831

Bryan B, Gao L, Ye Y, Sun X, Connor J, Crossman N, Stafford Smith M, Wu J, He C, Yu D, Liu Z, Li A, Huang Q, Ren H, Deng X, Zheng H, Niu J, Han G, Hou X (2018) China's response to a national land-system sustainability emergency. Nature. https://doi.org/10.1038/s41586-018-0280-2

Callon M, Courtial J-P, Turner WA, Bauin S (1983) From translations to problematic networks: an introduction to co-word analysis. Inf Behav 22:191–235

Cao Q, Wu J, Yu D, Wang W (2019) The biophysical effects of the vegetation restoration program on regional climate metrics in the Loess Plateau, China. Agric For Meteorol 268:169–180

Chen J, John R, Sun G, Fan P, Henebry GM, Fernandez-Gimenez ME, Zhang Y, Park H, Tian L, Groisman P, Ouyang Z, Allington G, Wu J, Shao C, Amarjargal A, Dong G, Gutman G, Huettmann F, Lafortezza R, Crank C, Qi J (2018) Prospects for the sustainability of social-ecological systems (SES) on the Mongolian plateau: five critical issues. Environ Res Lett. https://doi.org/10.1088/1748-9326/aaf27b

Chen X, Hao B, Jing X, He JS, Ma W, Zhu B (2019) Minor responses of soil microbial biomass, community structure and enzyme activities to nitrogen and phosphorus addition in three grassland ecosystems. Plant Soil 444:21–37

Cobo MJ, Lopez-Herrera AG, Herrera-Viedma E, Herrera F (2011) An approach for detecting, quantifying, and visualizing the evolution of a research field: a practical application to the Fuzzy Sets Theory field. J Informetr 5:146–166

Deng X, Huang J, Huang Q, Rozelle S, Gibson J (2011) Do roads lead to grassland degradation or restoration? A case study in Inner Mongolia, China. Environ Dev Econ 16:751–773

Dong S, Wolf SA, Lassoie JP, Liu SL, Long RJ, Yi SL, Jasra AW, Phuntsho K (2017) Bridging the gaps between science and policy for the sustainable management of rangeland resources in the developing world. Bioscience 67:656–663

Fang X, Zhou B, Tu X, Ma Q, Wu J (2018) What kind of a science is sustainability science? An evidence-based reexamination. Sustainability. https://doi.org/10.3390/su10051478

Feng G, Yan H, Yang X (2019) Climate and food diversity as drivers of mammal diversity in Inner Mongolia. Ecol Evol 9:2142–2148

Guo Y, Du Q, Li G, Ni Y, Zhang Z, Ren W, Hou X (2016) Soil phosphorus fractions and arbuscular mycorrhizal fungi diversity following long-term grazing exclusion on semi-arid steppes in Inner Mongolia. Geoderma 269:79–90

Hu Y, Huang J, Hou L (2019) Impacts of the grassland ecological compensation policy on household livestock production in China: an empirical study in Inner Mongolia. Ecol Econ 161:248–256

Inner Mongolia-Ningxia Joint Inspection Group of Chinese Sciences of Academy (1985) Vegetation of Inner Mongolia. Science Publishing House, Beijing

Ji C, Li X, Jia Y, Wang L (2018) Dynamic assessment of soil water erosion in the three-north shelter forest region of China from 1980 to 2015. Eurasian Soil Sci 51:1533–1546

Jia X, Fu B, Feng X, Hou G, Liu Y, Wang X (2014) The tradeoff and synergy between ecosystem services in the Grain-for-Green areas in Northern Shaanxi, China. Ecol Indic 43:103–113

Jiang G, Han X, Wu J (2006) Restoration and management of the inner Mongolia grassland require a sustainable strategy. Ambio 35:269–270

Jiang Y, Zhang Q, Niu J, Wu J (2019) Pastoral population growth and land use policy has significantly impacted livestock structure in Inner Mongolia-A case study in the Xilinhot region. Sustainability. https://doi.org/10.3390/su11247208

Jones HP, Barber NA, Gibson DJ (2019) Is phylogenetic and functional trait diversity a driver or a consequence of grassland community assembly? J Ecol 107:2027–2032

Jordan SJ, Hayes SE, Yoskowitz D, Smith LM, Summers JK, Russell M, Benson WH (2010) Accounting for natural resources and environmental sustainability: linking ecosystem services to human well-being. Environ Sci Technol 44:1530–1536

Kates RW, Clark WC, Corell R, Hall JM, Jaeger CC, Lowe I, McCarthy JJ, Schellnhuber HJ, Bolin B, Dickson NM, Faucheux S, Gallopin GC, Grubler A, Huntley B, Jager J, Jodha NS, Kasperson RE, Mabogunje A, Matson P, Mooney H, Moore B, O'Riordan T, Svedin U (2001) Environment and development—sustainability science. Science 80-) 292:641–642

Kattge J, Boenisch G, Diaz S, Lavorel S, Prentice IC, Leadley P, Tautenhahn S, Werner GDA, Aakala T, Abedi M, Acosta ATR, Adamidis GC, Adamson K, Aiba M, Albert CH, Alcantara JM, Alcazar CC, Aleixo I, Ali H, Amiaud B, Ammer C, Amoroso MM, Anand M, Anderson C, Anten N, Antos J, Apgaua DMG, Ashman T-L, Asmara DH, Asner GP, Aspinwall M, Atkin O, Aubin I, Baastrup-Spohr L, Bahalkeh K, Bahn M, Baker T, Baker WJ, Bakker JP, Baldocchi D, Baltzer J, Banerjee A, Baranger A, Barlow J,

Barneche DR, Baruch Z, Bastianelli D, Battles J, Bauerle W, Bauters M, Bazzato E, Beckmann M, Beeckman H, Beierkuhnlein C, Bekker R, Belfry G, Belluau M, Beloiu M, Benavides R, Benomar L, Berdugo-Lattke ML, Berenguer E, Bergamin R, Bergmann J, Carlucci MB, Berner L, Bernhardt-Roemermann M, Bigler C, Bjorkman AD, Blackman C, Blanco C, Blonder B, Blumenthal D, Bocanegra-Gonzalez KT, Boeckx P, BohlmanS Boehning-Gaese K, Boisvert-Marsh L, Bond W, Bond-Lamberty B, Boom A, Boonman CCF, Bordin K, Boughton EH, Boukili V, Bowman DMJS, Bravo S, Brendel MR, Broadley MR, Brown KA, Bruelheide H, Brumnich F, Bruun HH, Bruy D, Buchanan SW, Bucher SF, Buchmann N, Buitenwerf R, Bunker DE, Buerger J, Burrascano S, Burslem DFRP, Butterfield BJ, Byun C, Marques M, Scalon MC, Caccianiga M, Cadotte M, Cailleret M, Camac J, Julio Camarero J, Campany C, Campetella G, Campos JA, Cano-Arboleda L, Canullo R, Carbognani M, Carvalho F, Casanoves F, Castagneyrol B, Catford JA, Cavender-Bares J, Cerabolini BEL, Cervellini M, Chacon-Madrigal E, Chapin K, Chapin FS, Chelli S, Chen S-C, Chen A, Cherubini P, Chianucci F, Choat B, Chung K-S, Chytry M Ciccarelli D, Coll L, Collins CG, Conti L, Coomes D, Cornelissen JHC, Cornwell WK, Corona P, Coyea M, Craine J, Craven D, Cromsigt JPGM, Csecserits A Cufar K, Cuntz M, da Silva AC, Dahlin KM, Dainese M, Dalke I, Dalle Fratte M, Anh Tuan D-L, Danihelka J, Dannoura M, Dawson S, de Beer AJ, FrutosA De, De Long JR, Dechant B, Delagrange S, Delpierre N, Derroire G, Dias AS, Diaz-Toribio MH, Dimitrakopoulos PG, Dobrowolski M, Doktor D, Drevojan P, Dong N, Dransfield J, Dressler S, Duarte L, Ducouret E, Dullinger S, Durka W, Duursma R, Dymova O, E-Vojtko A, Eckstein RL, Ejtehadi H, Elser J, Emilio T, Engemann K, Erfanian MB, Erfmeier A, Esquivel-Muelbert A, Esser G, Estiarte M, Domingues TF, Fagan WF, Fagundez J, Falster DS, Fan Y, Fang J, Farris E, Fazlioglu F, Feng Y, Fernandez-Mendez F, Ferrara C, Ferreira J, Fidelis A, Finegan B, Firn J, Flowers TJ, Flynn DFB, Fontana V, Forey E, Forgiarini C, FrancoisL, Frangipani M, Frank D, Frenette-Dussault C, Freschet GT, Fry EL, Fyllas NM, Mazzochini GG, Gachet S, Gallagher R, Ganade G, Ganga F, Garcia-Palacios P, Gargaglione V, Garnier E, Luis Garrido J, Luis de Gasper A, Gea-Izquierdo G, Gibson D, Gillison AN, Giroldo A, Glasenhardt M-C, Gleason S, Gliesch M, Goldberg E, Goeldel B, Gonzalez-Akre E, Gonzalez-Andujar JL, Gonzalez-Melo A, Gonzalez-Robles A, Graae BJ, Granda E, Graves S, Green WA, Gregor T, Gross N, Guerin GR, Guenther A, Gutierrez AG, Haddock L, Haines A, Hall J, Hambuckers A, Han W, Harrison SP, Hattingh W, Hawes JE, He T, He P, Heberling JM, Helm A, Hempel S, Hentschel J, Herault B, Heres A-M, Herz K, Heuertz M, Hickler T, Hietz P, Higuchi P, Hipp AL, Hirons A, Hock M, Hogan JA, Holl K, Honnay O, Hornstein D, Hou E, Hough-Snee N, Hovstad KA, Ichie T, Igic B, Illa E, Isaac M, Ishihara M, Ivanov L, Ivanova L, Iversen CM, Izquierdo J, Jackson RB, Jackson B, Jactel H, Jagodzinski AM, Jandt U, Jansen S, Jenkins T, Jentsch A, Jespersen JRP, Jiang G-F, Johansen JL, Johnson D, Jokela EJ, Joly CA, Jordan GJ, Joseph GS, Junaedi D, Junker RR, Justes E, Kabzems R, Kane J, Kaplan Z, Kattenborn T, Kavelenova L, Kearsley E, Kempel A, Kenzo T, Kerkhoff A, Khalil MI, Kinlock NL, Kissling WD, Kitajima K, Kitzberger T, Kjoller R, Klein T, Kleyer M, Klimesova J, Klipel J, Kloeppel B, Klotz S, Knops JMH, Kohyama T, Koike F, Kollmann J, Komac B, Komatsu K, Koenig C, Kraft NJB, Kramer K, Kreft H, Kuehn I, Kumarathunge D, Kuppler J, Kurokawa H, Kurosawa Y, Kuyah S, Laclau J-P, Lafleur B, Lallai E, Lamb E, Lamprecht A, Larkin DJ, Laughlin D, Le Bagousse-Pinguet Y, le Maire G, le Roux PC, le Roux E, Lee T, Lens F, Lewis SL, Lhotsky B, Li Y, Li X, Lichstein JW, Liebergesell M, Lim JY, Lin Y-S, Linares JC, Liu C, Liu D, Liu U, Livingstone S, Llusia J, Lohbeck M, Lopez-Garcia A, Lopez-Gonzalez G, Lososova Z, Louault F, Lukacs BA, Lukes P, Luo Y, Lussu M, Ma S, Pereira CMR, Mack M, Maire V, Makela A, Makinen H, Mendes Malhado AC, Mallik A, Manning P, Manzoni S, Marchetti Z, Marchino L, Marcilio-Silva V, Marcon E, Marignani M, Markesteijn L, Martin A, Martinez-Garza C, Martinez-Vilalta J, Maskova T, Mason K, Mason N, Massad TJ, Masse J, Mayrose I, McCarthy J, McCormack ML, McCulloh K, McFadden IR, McGill BJ, McPartland MY, Medeiros JS, Medlyn B, Meerts P, Mehrabi Z, Meir P, Melo FPL, Mencuccini M, Meredieu C, Messier J, Meszaros I, Metsaranta J, Michaletz ST, Michelaki C, Migalina S, Milla R, Miller JED, Minden V, Ming R, Mokany K, Moles AT, Molnar AV, Molofsky J, Molz M, Montgomery RA, Monty A, Moravcova L, Moreno-Martinez A, Moretti M, Mori AS, Mori S, Morris D, Morrison J, Mucina L, Mueller S, Muir CD, Mueller SC, Munoz F, Myers-Smith IH, Myster RW, Nagano M, Naidu S, Narayanan A, Natesan B, Negoita L, Nelson AS, Neuschulz EL, Ni J, Niedrist G, Nieto J, Niinemets U, Nolan R, Nottebrock H, Nouvellon Y, Novakovskiy A, Nystuen KO, O'Grady A, O'Hara K, O'Reilly-Nugent A, Oakley S, Oberhuber W, Ohtsuka T, Oliveira R, Ollerer K, Olson ME, Onipchenko V, Onoda Y, Onstein RE, Ordonez JC, Osada N, Ostonen I, Ottaviani G, Otto S, Overbeck GE, Ozinga WA, Pahl AT, Paine CET, Pakeman RJ, Papageorgiou AC, Parfionova E, Paertel M, Patacca M, Paula S, Paule J, Pauli H, Pausas JG, Peco B, Penuelas J, Perea A, Luis Peri P, Petisco-Souza AC, Petraglia A, Petritan AM, Phillips OL, Pierce S, Pillar VD, Pisek J, Pomogaybin A, Poorter H, Portsmuth A, Poschlod P, Potvin C, Pounds D, Powell AS, Power SA, Prinzing A, Puglielli G, Pysek P, Raevel V, Rammig A, Ransijn J, Ray CA, Reich PB, Reichstein M, Reid DEB, Rejou-Mechain M, Resco de DiosV, Ribeiro S, Richardson S, Riibak K, Rillig MC, Riviera F, Robert EMR, Roberts S, Robroek B, Roddy A, Rodrigues AV, Rogers A, Rollinson E, Rolo V, Roemermann C, Ronzhina D, Roscher C, Rosell JA, Rosenfield MF, Rossi C, Roy DB, Royer-Tardif S, Rueger N, Ruiz-Peinado R, Rumpf SB, Rusch GM, RyoM, Sack L, Saldana A, Salgado-Negret B, Salguero-Gomez R, Santa-Regina I, Carolina Santacruz-Garcia A, Santos J, Sardans J, Schamp B, Scherer-Lorenzen M, Schleuning M, Schmid B, Schmidt M, Schmitt S, Schneider JV, Schowanek SD, Schrader J, Schrodt F, Schuldt B, Schurr F, Selaya Garvizu G, Semchenko M, Seymour C, Sfair JC, Sharpe JM, Sheppard CS, Sheremetiev S, Shiodera S, Shipley B, Shovon TA, Siebenkaes A, Carlos S, Silva V, Silva M, Sitzia T, Sjoman H, Slot M, Smith NG, Sodhi D, Soltis P, Soltis D, Somers B, Sonnier G, Sorensen MV, Sosinski EE, Jr.,

Soudzilovskaia NA, Souza AF, Spasojevic M, Sperandii MG, Stan AB, Stegen J, Steinbauer K, Stephan JG, Sterck F, Stojanovic DB, Strydom T, Laura Suarez M, Svenning J-C, Svitkova I, Svitok M, Svoboda M, Swaine E, Swenson N, Tabarelli M, Takagi K, Tappeiner U, Tarifa R, Tauugourdeau S, Tavsanoglu C, te Beest M, Tedersoo L, Thiffault N, Thom D, Thomas E, Thompson K, Thornton PE, Thuiller W, Tichy L, Tissue D, Tjoelker MG, Tng DYP, Tobias J, Torok P, Tarin T, Torres-Ruiz JM, Tothmeresz B, Treurnicht M, Trivellone V, Trolliet F, Trotsiuk V, Tsakalos JL, Tsiripidis I, Tysklind N, Umehara T, Usoltsev V, Vadeboncoeur M, Vaezi J, Valladares F, Vamosi J, vanBodegom PM, van Breugel M, Van Cleemput E, van de Weg M, van der Merwe S, van der Plas F, van der Sande MT, van Kleunen M, Van Meerbeek K, Vanderwel M, Vanselow KA, Varhammar A, Varone L, Vasquez Valderrama MY, Vassilev K, Vellend M, Veneklaas EJ, Verbeeck H, Verheyen K, Vibrans A, Vieira I, Villacis J, Violle C, Vivek P, Wagner K, Waldram M, Waldron A, Walker AP, Waller M, Walther G, Wang H, Wang F, Wang W, Watkins H, Watkins J, Weber U, Weedon JT, Wei L, Weigelt P, Weiher E, Wells AW, Wellstein C, Wenk E, Westoby M, Westwood A, White PJ, Whitten M, Williams M, Winkler DE, Winter K, Womack C, Wright IJ, Wright SJ, Wright J, Pinho BX, Ximenes F, Yamada T, Yamaji K, Yanai R, Yankov N, Yguel B, Zanini KJ, Zanne AE, Zeleny D, Zhao Y-P, Zheng J, Zheng J, Zieminska K, Zirbel CR, Zizka G, Zo-Bi IC, Zotz G, Wirth C, Nutrient N (2020) TRY plant trait database—enhanced coverage and open access. Glob Change Biol 26:119–188

Kemp DR, Han G, Hou F, Hou X, Li Z, Sun Y, Wang Z, Wu J, Zhang X, Zhang Y, Gong X (2018) Sustainable management of Chinese grasslands-issues and knowledge. Front Agric Sci Eng 5:9–23

Kemp DR, Han G, Hou X, Michalk DL, Hou F, Wu J, Zhang Y (2013) Innovative grassland management systems for environmental and livelihood benefits. Proc Natl Acad Sci USA 110:8369–8374

King MF, Reno VF, Novo E (2014) The concept, dimensions and methods of assessment of human well-being within a socioecological context: a literature review. Soc Indic Res 116:681–698

Li A, Wu J, Zhang X, Xue J, Liu Z, Han X, Huang J (2018) China's new rural "separating three property rights" land reform results in grassland degradation: evidence from Inner Mongolia. Land Use policy 71:170–182

Li B (1997) The rangeland degradation in North China and its preventive strategies (in chinese). Sci Agric Sin 30:1–9

Li W, Huntsinger L (2011) China's grassland contract policy and its impacts on herder ability to benefit in Inner Mongolia: tragic feedbacks. Ecol Soc 16:1

Li X, Tian M, Wang H, Wang H, Yu J (2014) Development of an ecological security evaluation method based on the ecological footprint and application to a typical steppe region in China. Ecol Indic 39:153–159

Liao C, Qiu J, Chen B, Chen D, Fu B, Georgescu M, He C, Jenerette GD, Li X, Li X, Li X, Qiuying B, Shi P, Wu J (2020) Advancing landscape sustainability science: theoretical foundation and synergies with innovations in methodology, design, and application. Landsc Ecol 35:1–9

Liu Q, Buyantuev A, Wu J, Niu J, Yu D, Zhang Q (2018) Intensive land-use drives regional-scale homogenization of plant communities. Sci Total Environ 644:806–814

Liu Q, Zhang Q, Yan Y, Zhang X, Niu J, Svenning JC (2020a) Ecological restoration is the dominant driver of the recent reversal of desertification in the Mu Us Desert (China). J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.122241

Liu Y, Zhang Q, Liu Q, Yan Y, Hei W, Yu D, Wu J (2020b) Different household livelihood strategies and influencing factors in the Inner Mongolian Grassland. Sustainability. https://doi.org/10.3390/su12030839

Ma Q, He C, Fang X (2018) A rapid method for quantifying landscape-scale vegetation disturbances by surface coal mining in arid and semiarid regions. Landsc Ecol 33:2061–2070

Mao D, Wang Z, Wu B, Zeng Y, Luo L, Zhang B (2018) Land degradation and restoration in the arid and semiarid zones of China: quantified evidence and implications from satellites. Land Degrad Dev 29:3841–3851

Opdam P, Luque S, Nassauer J, Verburg PH, Wu J (2018) How can landscape ecology contribute to sustainability science? Landsc Ecol 33:1–7

Pettitt AN (1979) A non-parametric approach to the change-point problem. J R Stat Soc 28:126–135

Ramanathan V, Feng Y (2009) Air pollution, greenhouse gases and climate change: global and regional perspectives. Atmos Environ 43:37–50

Ren J, Xu G, Li X, Lin H, Tang Z (2016) Trajectory and prospect of China's prataculture (in chinese). Chin Sci Bull 61:178

Reynolds JF, Stafford Smith DM, Lambin EF, Turner BL, Mortimore M, Batterbury SPJ, Downing TE, Dowlatabadi H, Fernandez RJ, Herrick JE, Huber-Sannwald E, Jiang H, Leemans R, Lynam T, Maestre FT, Ayarza M, Walker B (2007) Global desertification: building a science for dryland development. Science 316:847–851

Robinson BE, Li P, Hou X (2017) Institutional change in social-ecological systems: the evolution of grassland management in Inner Mongolia. Glob Environ Change-Human Policy Dimens 47:64–75

Sørensen TA (1948) A method of establishing groups of equal amplitude in plant sociology based on similarity of species and its application to analyses of the vegetation on Danish commons. Biologiske Skrifter/Kongelige Danske Videnskabernes Selskab 5:1–34

Schoenbach P, Wan H, Schiborra A, Gierus M, Bai Y, Mueller K, Glindemann T, Wang C, Susenbeth A, Taube F (2009) Short-term management and stocking rate effects of grazing sheep on herbage quality and productivity of Inner Mongolia steppe. Crop Pasture Sci 60:963–974

Shang C, Wu T, Huang G, Wu J (2019) Weak sustainability is not sustainable: socioeconomic and environmental assessment of Inner Mongolia for the past three decades. Resour Conserv Recycl 141:243–252

Suttie JM, Reynolds SG, Batello C (2005) Grasslands of the world. Food and Agriculture Organization of the United Nations, Rome

Tao S, Fang J, Zhao X, Zhao S, Shen H, Hu H, Tang Z, Wang Z, Guo Q (2015) Rapid loss of lakes on the Mongolian Plateau. Proc Natl Acad Sci USA 112:2281–2286

Vargas SA, Telles Esteves GR, Macaira PM, Bastos BQ, Cyrino Oliveira FL, Souza RC (2019) Wind power generation: A review and a research agenda. J Clean Prod 218:850–870
Wang L, Delgado-Baquerizo M, Wang DL, Isbell F, Liu J, Feng C, Liu JS, Zhong ZW, Zhu H, Yuan X, Chang Q, Liu C (2019) Diversifying livestock promotes multidiversity and multifunctionality in managed grasslands. Proc Natl Acad Sci USA 116:6187–6192
Wang X, Li FY, Tang K, Wang Y, Suri G, Bai Z, Baoyin T (2020) Land use alters relationships of grassland productivity with plant and arthropod diversity in Inner Mongolian grassland. Ecol Appl. https://doi.org/10.1002/eap.2052
Wang Z, Deng X, Song W, Li Z, Chen J (2017) What is the main cause of grassland degradation? A case study of grassland ecosystem service in the middle-south Inner Mongolia. CATENA 150:100–107
WCED (1987) Our common future. Oxford University Press, Oxford, UK
Wu J (2006) Landscape ecology, cross-disciplinarity, and sustainability science. Landsc Ecol 21:1–4
Wu J (2013) Landscape sustainability science: ecosystem services and human well-being in changing landscapes. Landsc Ecol 28:999–1023
Wu J (2014) Urban ecology and sustainability: the state-of-the-science and future directions. Landsc Urban Plan 125:209–221
Wu J (2019) Linking landscape, land system and design approaches to achieve sustainability. J Land Use Sci 14:173–189
Wu J, Loucks OL (1992) Xilingele (The Xilingol Grassland). In: The US National Research Council (ed) Grasslands and grassland sciences in Northern China. National Academy Press, Washington, D.C., pp 67–84
Wu J, Zhang Q, Li A, Liang C (2015) Historical landscape dynamics of Inner Mongolia: patterns, drivers, and impacts. Landsc Ecol 30:1579–1598
Yan Y, Zhang Q, Buyantuev A, Liu Q, Niu J (2020) Plant functional β diversity is an important mediator of effects of aridity on soil multifunctionality. Sci Total Environ Online. https://doi.org/10.1016/j.scitotenv.2020.138529
Yang G, Liu N, Lu WJ, Wang S, Kan HM, Zhang YJ, Xu L, Chen YL (2014) The interaction between arbuscular mycorrhizal fungi and soil phosphorus availability influences plant community productivity and ecosystem stability. J Ecol 102:1072–1082
Ye C, Chen DM, Hall SJ, Pan S, Yan XB, Bai TS, Guo H, Zhang Y, Bai YF, Hu SJ (2018) Reconciling multiple impacts of nitrogen enrichment on soil carbon: plant, microbial and geochemical controls. Ecol Lett 21:1162–1173
Yin H, Udelhoven T, Fensholt R, Pflugmacher D, Hostert P (2012) How normalized difference vegetation index (NDVI) trends from advanced very high resolution radiometer (AVHRR) and Systeme Probatoire d'Observation de la Terre VEGETATION (SPOT VGT) time series differ in agricultural areas: an Inner Mongolian case study. Remote Sens 4:3364–3389
Yuan F, Wu J, Li A, Rowe H, Bai YF, Huang J, Han X (2015) Spatial patterns of soil nutrients, plant diversity, and aboveground biomass in the Inner Mongolia grassland: before and after a biodiversity removal experiment. Landsc Ecol 30:1737–1750
Zhang Q, Hou XY, Li FYH, Niu JM, Zhou YL, Ding Y, Zhao LQ, Li X, Ma WJ, Kang S (2014) Alpha, beta and gamma diversity differ in response to precipitation in the Inner Mongolia grassland. PLoS ONE. https://doi.org/10.1371/journal.pone.0093518
Zhang Q, Wu J, Buyantuev A, Niu J, Zhou Y, Ding Y, Kang S, Ma W (2016) Plant species diversity is correlated with climatic factors differently at the community and the functional group levels: a case study of desert steppe in Inner Mongolia, China. Plant Biosyst 150:121–123
Zhang Q, Buyantuev A, Li FY, Jiang L, Niu JM, Ding Y, Kang S, Ma WJ (2017a) Functional dominance rather than taxonomic diversity and functional diversity mainly affects community aboveground biomass in the Inner Mongolia grassland. Ecol Evol 7:1605–1615
Zhang X, Johnston ER, Barberan A, Ren Y, Lu X, Han X (2017b) Decreased plant productivity resulting from plant group removal experiment constrains soil microbial functional diversity. Glob Change Biol 23:4318–4332
Zhang Q, Zhao Y, Li Y (2019) Optimal herdsmen household management modes in a typical steppe region of Inner Mongolia, China. J Clean Prod 231:1–9
Zhao H, Zhou R, Su Y, Zhang H, Zhao L, Drake S (2007) Shrub facilitation of desert land restoration in the Horqin Sand Land of Inner Mongolia. Ecol Eng 31:1–8
Zhao J (2015) Analysis on carbon sequestration and carbon sink increment potential of rangelands in Inner Mongolia. China Social Sciences Press, Beijing
Zhao YY, Wu J, He C, Ding G (2017) Linking wind erosion to ecosystem services in drylands: a landscape ecological approach. Landsc Ecol 32:2399–2417
Zhao Y, Zhang Q, Li FY (2019) Patterns and drivers of household carbon footprint of the herdsmen in the typical steppe region of inner Mongolia, China: a case study in Xilinhot City. J Clean Prod 232:408–416
Zhao YY, Liu ZF, Wu JG (2020) Grassland ecosystem services: a systematic review of research advances and future directions. Landsc Ecol 35:793–814
Zhou B, Wu J, Anderies JM (2019) Sustainable landscapes and landscape sustainability: a tale of two concepts. Landsc Urban Plan 189:274–284
Zhou Z, Sun O, Luo Z, Jin H, Chen Q, Han X (2008) Variation in small-scale spatial heterogeneity of soil properties and vegetation with different land use in semiarid grassland ecosystem. Plant Soil 310:103–112